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THE IMPACT OF INTERNET GIS ON ACCESS TO WATER QUALITY
INFORMATION

A Dissertation

Presented to

the Faculty of Natural Sciences and Mathematics

University of Denver

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

by

Joseph H. Hoover

June 2014

Advisor: Paul C. Sutton

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Title: THE IMPACT OF INTERNET GIS ON ACCESS TO WATER QUALITY INFORMATION

Advisor: Paul C. Sutton

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Abstract

Empowering citizens to comprehend complex environmental issues affecting their daily lives is essential to sustaining a healthy and informed public. The work of many environmental nongovernmental organizations (ENGOS) and institutions of higher education (IHEs) center around helping their stakeholders become informed of, and in turn, better understand complex environmental problems. However, providing individual stakeholders with knowledge about environmental issues that is easily accessible and understandable represents a recurring challenge in today's society. As a result, a gap continues to exist between that which is known about environmental problems and the public's awareness and understanding of those issues. Arsenic contamination of drinking water from privately owned groundwater wells in rural areas of the southwest the United States is one such environmental issue, which is the focus of this research project.

Results from this study demonstrate that an Internet-based GIS application represents a promising tool for informing stakeholders of selected water quality issues and helping stakeholders comprehend the scope of arsenic found in drinking water in rural areas. Specifically, findings from this research suggest that the interactive environment of an Internet GIS is an easy to use technology that facilitates the visualization of arsenic water quality impairment in an accessible format for stakeholders. Feedback from ENGO and IHE professionals (who were the target population in this study) indicated that an Internet GIS application, such as the one used in this project,

represents one method to inform stakeholders of drinking water quality issues. This, in turn, contributes to reducing the gap between known scientific information about environmental issues and stakeholder knowledge of the facts and consequences associated with those concerns.

Results from this study inform an important initial step in reducing the knowledge gap (i.e., determining ENGO and IHE professionals' perspectives about the value of use of an Internet GIS for engaging with public stakeholders), leading to the subsequent task of ensuring that public stakeholders are aware of the opportunities to use Internet GIS to become more informed about water quality issues. To advance the findings from this project, additional research is needed to further clarify best practices that ENGO and IHE professionals may employ to disseminate an easily accessible Internet GIS for water quality from rural, unregulated sources. Additional need exists to gather and compare the perceptions of stakeholders with the perspectives of ENGO and IHE professionals to best clarify the use of Internet GIS as a tool to disseminate unregulated drinking water quality information to rural water users.

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Chapter One: Introduction

Background of the Study

Access to safe and reliable drinking water is critical for maintaining human health (WHO, 2003), especially for people whose drinking water sources are unregulated and contain dangerous contaminants. Public water systems in the United States deliver drinking water to 258 million people and this water is regulated by rules articulated in the Safe Drinking Water Act (SDWA) of 1974. A public water system is one that provides water for human consumption to 15 or more connections or 25 or more people per year (Kenny et al., 2009). However, a significant number of people (i.e., approximately 43 million Americans) acquire their drinking water from private sources, which unlike public sources, are not regulated by the SDWA. As a result, the quality of drinking water from these unregulated sources remains unknown since many well owners fail to test their water for contaminants regularly (Backer & Tosta, 2011). According to the U.S. Geological Survey, 98% of self-supplied domestic drinking water is supplied by groundwater resources (Kenny et al., 2009), and nearly half of the residents who use these unregulated drinking water sources (UDWS) live in rural areas (U.S. Census Bureau, 2013).

The quality of water from unregulated sources is of particular concern within rural areas of the United States since contaminants such as arsenic, uranium, nitrates and microorganisms affect more than one in five UDWS (DeSimone, Hamilton, & Billiom,

2009). While consumption of contaminated groundwater poses a threat to human health, the threat may remain undetected; many UDWS well owners in rural areas infrequently test for water contaminants, are unaware of the need to test for contaminants or fail to understand the test results and their implications (Kreutzwiser et al., 2011).

Arsenic is one contaminant affecting the water quality of rural residents' UDWS. Previous studies at the national level in the United States have reported that 6-11% of self-supplied domestic groundwater wells have arsenic levels exceeding the SDWA maximum contaminant level (10 µg per liter)(Ayotte, Gronberg, & Apodaca, 2011; DeSimone et al., 2009; Focazio, Tipton, Shapiro, & Geiger, 2006). Arsenic is one of the most common groundwater contaminants in Arizona, New Mexico and Navajo Nation (Camacho, Gutiérrez, Alarcón-Herrera, de Loudres Villlba, & Deng, 2011; Fennema, 2013; Uhlman, Rock, & Artiola, 2009). Increasingly, groundwater pollution results in the abandonment of wells due to contamination (Perry & Vanderklein, 1996), which in turn impacts safe drinking water supply options and access.

Problem Statement

Unlike SDWA procedures stipulated for public water sources, environmental decision-making associated with rural UDWS is more challenging due to widely dispersed well locations, isolated water users and disparate data sources from multiple regulatory agencies and private water testing companies. For typical rural residents, acquiring water quality information about their private groundwater wells is often difficult, and alerting users to the existence of previous water quality results for private wells and the associated problems remains a continuing challenge (A. Q. Jones et al., 2006). The lack of resource user knowledge and awareness about water quality is of

particular concern (Charrois, 2010; Hynds, Misstear, & Gill, 2013). Previous research demonstrated that access to water quality information may influence user behavior and compel users to test their drinking water quality, especially when the water is supplied by an unregulated water source in a rural area (Chappells et al., 2014; Charrois, 2010; A. Q. Jones et al., 2006; Poe, van Es, VandenBerg, & Bishop, 1998).

Therefore, providing individual stakeholders with knowledge about water quality issues that is easily accessible and understandable represents a recurring challenge in today's society. As a result, a gap continues to exist between that which is known about environmental challenges and the public's awareness and understanding of those known issues, particularly related to high levels of arsenic in UDWS located in rural locations in the United States.

Purpose of Study

A foundational scientific understanding of contamination is necessary to recommend, develop, and adopt effective policies to decrease contaminant exposure and protect human health (Reed, 2008). However, as discussed, access to environmental data from multiple data sources in assorted formats is challenging for many decision-makers and the general public. Millions of Americans, almost exclusively in rural areas, rely on UDWS with unknown water quality. Some of these water sources have been tested for contamination although these results may be unavailable to resource users, or the results may be presented in a manner that is incomprehensible to members of the general public (Kreutzwiser et al., 2011; Simpson, 2004).

A gap exists between what is known about the quality of water resources and what resources users know about their drinking water (Backer & Tosta, 2011). As a

result, a need exists to identify tools for bridging this knowledge gap by helping people who rely on UDWS to better understand the quality of their drinking water in rural areas. Internet-based Geographic information systems (GIS) technology is one contemporary tool that may provide resource users and stakeholders with groundwater quality information to make informed drinking water decisions.

Researchers have demonstrated that geospatial technology, such as GIS, benefits citizen education and decision-making due to its (a) ability to provide access to environmental data, (b) capacity to use environmental models through a user friendly interface, and (c) powerful visualization capabilities (Argent, 2004; Dobson, 1997; Haklay, 2003; Jankowski, 2009; Sweeney, 1998; Ventura, 1995). GIS is a software system that enables users to organize and analyze spatial datasets (Longley, Goodchild, Maguire, & Rhind, 2005). Although GIS technology is useful for environmental management, it remains underutilized in the decision-making process due to its complexity and the specialized training necessary to use it appropriately (Desai, Greenbaum, & Kim, 2009). The need for training is compounded by limited environmental awareness, dispirited technology access (Sieber, 2006) or diminishing interest among resource users and decision makers who could use geospatial technology to better understand the quality of natural resources and the environment (Pocewicz, Brown, Nielsen-Pincus, & Schnitzer, 2012).

A more user friendly and less technically challenging method of engaging stakeholders is necessary to provide water quality information to resource users. Internet GIS is one such tool that enables non-expert users to benefit from visualization and is accessible through an Internet browser (Dangermond & Maidment, 2010; Peng & Tsou,

2003). It also reduces the need for technical training and specialized software that prevents the general public from using GIS software and tools (AlSabhan, 2003). Furthermore, an Internet GIS enables users to explore a decision problem and to formulate decision outcomes (Carver, Evans, Kingston, & Turton, 2000), by dynamically visualizing water resources information, thereby expanding access to environmental data.

Research Scope

Though issues of contaminated drinking water represent a breadth and depth that span many rural regions of the United States (and internationally), the scope of this research is delimited to two recurring issues in connection with rural drinking water in the southwestern United States:

1. Arsenic groundwater occurrence
2. Lack of easily accessible information to improve awareness about arsenic contamination.

To address Issue 1, I used existing quantitative data provided by the United States and Navajo Nation Environmental Protection Agencies that reflect the drinking water conditions found in the Navajo Nation (NN). These data represent conditions specific to the NN, yet also provide an example of the type of water quality challenges that residents in many rural areas of the western United States face when acquiring drinking water from UDWS. Additionally, these water quality data reflect a rural location with extensive, low-level (concentrations lower than the SDWA maximum contaminant level) arsenic groundwater contamination affecting an at-risk population of people with limited supply options and access to information about their drinking water.

To address Issue 2, I created an Internet GIS application that dynamically visualized water quality information, accessible through an Internet browser, to illustrate arsenic contamination in an easily accessible format, followed by evaluation of the user experience and perspectives about the groundwater quality issue. In this study, arsenic groundwater contamination throughout the Navajo Nation (NN) was visualized as an example of the type of water quality challenges that exist for rural residents, including underserved populations, who use unregulated drinking water sources.

Research Population

Ultimately, the drinking water consumer is most affected by acquiring water quality information. However, the general public often fails to understand and address water related issues (Charrois, 2010). Fortunately, professionals from two types of educational entities provide timely and accurate information to resource users:

- Environmental nongovernmental Organizations (ENGOS) (Singh & Rahman, 2010);
- Institutions of higher education (IHEs) (Mills & Clark, 2001).

ENGOS and IHEs assume an important role in the provision of GIS technology and geospatial data for use in environmental decision-making processes (Sieber, 2002).

Sawicki and Peterman (2002) refer to organizations without direct community involvement and the capacity for GIS services as data intermediaries, which may include government agencies, university centers, nongovernmental organizations and non-profit organizations. Since ENGOS and IHEs are integral components of environmental

management (Agarwal, 2008), and essential to informing the public of potential water quality contamination issues, the study participants were drawn from a pool of research and advocate professionals with water resources knowledge from ENGOs and IHEs that work to address water resource issues in the western United States.

Based on my review of existing NGO typologies (Fox, 1987; Vakil, 1997), I selected employees from ENGOs with an orientation towards advocacy, development, education, or research and operate at the local or regional scale. I also used sectoral focus to identify relevant ENGOs in the western United States and selected organizations that investigate water resource or water quality problems. I also included individuals associated with institutions of higher education (IHE). Recruited IHE participants included researchers who actively investigate water quality issues from a physical science, social or health perspective. I identified IHE professionals in the western United States primarily through membership directories of the Association of American Geographers and the American Water Resources Association.

The study population is delimited to individuals from these entities as the entry point for evaluating the capacity and potential for using Internet GIS technology to inform the general public about water quality issues associated with UDWS in rural regions. The rationale for selecting this initial population is found in each selected entity's capacity to reach the masses of people to whom each serves by presenting contemporary information to inform stakeholders about arsenic contamination in rural drinking water supplies.

Research Questions And Methods

My examination of disseminating arsenic drinking water contamination information in an easily accessible format is guided by three research questions:

1. Which features within an Internet GIS application facilitate the dissemination of groundwater quality information to users?
2. To what extent does an Internet GIS application inform users about an unregulated drinking water source water quality issue?
3. Do ENGO and IHE professionals perceive an Internet GIS application to be useful for increasing issue awareness and conveying water quality information to stakeholders?

I developed an Internet GIS application to visualize arsenic groundwater contamination of unregulated drinking water sources on the Navajo Nation. To answer the first two research questions I then invited study participants to use the application and complete a survey to assess their learning from the application. I also employed web analytics to evaluate how participants used the GIS. Additionally, I used Q Methodology to identify perspectives that ENGO and IHE professionals hold toward using Internet GIS applications to convey water quality information to stakeholders.

Study Area

The study area was limited to the Navajo Nation (Figure 1; GIS data from US EPA (2006)), which includes 27,425 square miles of land in Arizona, New Mexico and Utah, has a population of 173,667 and a population density of 6.33 people per square mile (Navajo Division of Health, 2013). Groundwater, stored in sedimentary rock

formations such as Coconino and Navajo Sandstone, is the source of 99% of drinking water on the NN (Cooley, Harshbarger, Akers, & Hardt, 1964; NN DWR, 2011).

According to the Navajo Nation EPA, 182 public water systems on the NN serve 12,000 acre-feet (AF) of drinking water annually to more 140,000 people (NNEPA, 2014).

Between 30 and 40% of residents do not have household access to public drinking water systems and haul their drinking water from unregulated sources (Leeper, 2003; US BOR, 2009). Due to the fact that many residents consume water from private wells, a need exists to help users understand their drinking water quality from the unregulated groundwater sources in this study area.



Figure 1: Boundaries of the Navajo Nation in the southwestern United States.

Water Quality Issue

Arsenic groundwater contamination is the water resource issue of interest in this study since it represents an important human health concern due to its carcinogenic properties and occurrence in groundwater throughout the United States. According to Comacho et al. (2011, p. 212) “arsenic is one of the most feared contaminants because of its high toxicity at small concentrations.” Geographically, arsenic groundwater occurrence in the United States is non-uniform, with the most widespread contamination occurring in the western US (Focazio, Welch, Watkins, Helsel, & Horn, 2000). In Arizona and New Mexico, arsenic is one of the most common groundwater contaminants (Uhlman et al., 2009) and it regularly exceeds the Safe Drinking Water Act maximum contaminant level (Hood, Towne, & Callaway, 2012). Nationally, approximately 7% of unregulated water wells provide drinking water with arsenic levels that exceed SDWA limits (DeSimone et al., 2009). Previous studies investigating water quality of rural, unregulated water sources on the Navajo Nation reported arsenic levels in groundwater that regularly exceeded the SDWA MCL (deLemos et al., 2009; Fennema, 2013; US EPA, 2006). Arsenic groundwater contamination of unregulated drinking water sources is a prevailing problem throughout the NN and presents public health challenges due to a large number of NN residents consuming drinking water from unregulated groundwater wells.

Limitations

A study such as this has limitations that provide boundaries for generalization of findings. The current study population includes only one segment of the potential stakeholders interested in UDWS quality problems, which includes citizens, decision-

makers, universities, grassroots organizations, community based organizations, nongovernmental organizations and others. The “public” is a multilayer concept (Schlossberg & Shuford, 2005) and for the present study only environmental NGO employees and institution of higher education staff were recruited as participants. Study participants were further limited to individuals with a publically available email address and a reliable Internet connection capable of loading and using the Internet GIS application. The study area was limited to the boundaries of the Navajo Nation. While the visualized UDWS water quality issue is representative of rural groundwater problems more generally, the study emphasized one specific area and did not visualize arsenic contamination in other areas of the United States.

This study was limited to arsenic groundwater contamination and did not comprehensively address other public health challenges associated with unregulated drinking water sources. Other water quality concerns exist in the study area, namely uranium and microbial contamination, which are beyond the scope of this study. Additionally, the environmental data for the study were provided by designated environmental monitoring agencies and reflect the most up to date non-proprietary information available.

Study Significance

Unregulated drinking water sources provide water to million of Americans; however, these water sources are subject to contamination from human and naturally occurring sources. Given that private well owners infrequently test their water for contaminants and that accessing previous water quality results is challenging, many residents unknowingly consume drinking water with potentially dangerous levels of

contaminants, especially arsenic. Several methods exist for communicating water quality information to resource users though few studies have applied geospatial technology to address this challenge. The purpose of this study is to evaluate the capacity of Internet GIS technology for increasing access to water quality information and raising issue awareness regarding arsenic contamination of UDWS. The present study is an initial step in filling the gap that exists between what is known about UDWS water quality and what resource users know about their drinking water. To fill this gap, the present study used Internet GIS technology to visualize arsenic groundwater contamination on the Navajo Nation in the southwest United States. The results of this study are applicable to private groundwater wells in rural areas of developed countries and have implications for the use of geospatial technology to convey water quality information to resource users.

Organization Of The Study

This study is presented in six chapters. Chapter One includes background for the study, the problem statement, purpose of the study, research scope and population, research questions and methods, study area, limitations and organization of study. Chapter Two includes a literature review regarding drinking water supply in the United States, the prevalence and challenges associated with unregulated drinking water sources and methods for disseminating water quality information. Chapter Three includes a discussion of the value of Internet GIS for disseminating water quality information associated with unregulated drinking water sources. Chapter Four describes an evaluation of the ability of Internet GIS to provide access to UDWS water quality data. Chapter Five details the perspective of ENGO and IHE professionals toward using Internet GIS to convey UDWS water quality information to their stakeholders. Lastly,

Chapter Six provides a summary of the important findings from this research and a discussion of future research directions.

Chapter Two: Literature Review

Introduction

The integrated nature of water resources management and planning necessitates a systematic and interdisciplinary approach to identify and resolve issues (Knapp, 1995). Water quality issues are challenging to address owing to the spatial heterogeneity of impacts, source ambiguity and challenges evaluating the magnitude of the problem (Engel, Srinivasan, Arnold, Rewerts, & Brown, 1993). Since many stakeholders develop their own understanding of water quality problems, misconceptions and misdirected solutions are commonly proposed that fail to address the underlying causes of water pollution. Basic, Rossiter and Bregat (2006) determined that inaccurate knowledge regarding the causes of water pollution often leads to actions that fail to solve the problem. In order to address misconceptions and limited understanding of water quality problems, greater access to environmental information is necessary.

Challenges associated with accessing and using environmental data for decision-making and modeling continue to exist. Tomasic and Simon (1997) observed that (a) for environmental phenomena, data may be nonexistent or insufficient for the specified problem, (b) locating existing data is challenging, and (c) access to data may be difficult due to financial cost, use rights or the need for extensive data pre-processing. Additionally, environmental data are frequently collected inconsistently (i.e., spatially, temporally or methods), making it difficult to use. The quality of environmental data is

frequently underreported and challenging to quantify. Contemporary water challenges require access to environmental data in a simple, user friendly manner to address the complexities of modern water management issues and competing goals among various stakeholders (Perkins, 2011).

Drinking Water

Approximately 153,000 public water systems exist in the United States that serve 25 or more people or 15 or more connections (US EPA, 2012). Of these systems, 53,000 are classified as community water systems (CWS) that serve the same population year round. CWS provide drinking water to more than 250 million people and are subject to all requirements of the Safe Drinking Water Act (SDWA). In addition to CWS, more than 19,000 non-transient, non-community water systems (NTNCWS) serve a known group of people for at least 6 months a year. However, 99% of these systems serve fewer than 3,300 people. Additionally, more than 86,000 transient non-community water systems (TNCWS) provide drinking water to a transitory population (i.e., campgrounds and gas stations). Approximately 95% of TNCWS serve less than 3,300 people (Tiemann, 2010).

The 1974 SDWA directed the United States Environmental Protection Agency (US EPA) to promulgate regulations for drinking water contaminants. Through the SDWA, the US Congress created several types of water quality standards including the maximum contaminant level goal (MCLG) and maximum contaminant level (MCL). The EPA has set MCLGs and MCLs for microorganisms, disinfectants, disinfection byproducts, inorganic chemicals, organic chemicals and radionuclides (US EPA, 2009). The maximum contaminant level goal (MCLG) is the chemical concentration at which no

adverse health effects are known to occur. The MCLG is based on human health and epidemiological data and is not enforceable.

The maximum contaminant level (MCL) however, is an enforceable standard that is set as close as possible to the MCLG while accounting for feasibility and economic challenges (Sullivan, Agardy, & Clark, 2005). The MCL is determined for large community water systems with special variances provided to smaller systems on a case-by-case basis. Operators of small systems may encounter problems meeting the proposed standards due to high costs associated with additional treatment. Variances are not provided for microbial contamination though other types of contaminants, such as chemical or radionuclides, may be eligible. For inorganic chemicals, the US EPA has set drinking water standards for 16 chemicals including arsenic.

Though regulation exists, many chemicals found in drinking water are unregulated by the Safe Drinking Water Act. To address human health risks associated with these unregulated chemicals, the U.S. Geological Survey established a set of health based screening levels (HBSL). These standards are set at levels that represent potential human health concerns and may be used to evaluate chemical levels in natural waters. For noncarcinogenic chemicals, the HBSL represents the maximum concentration level that is not expected to cause human health issues over the course of a lifetime (70 years). For carcinogenic chemicals, the HBSL represents a concentration that corresponds to a cancer risk level between 1 in one million and one in ten thousand. These screening levels are not water quality standards and are not enforceable; nevertheless, HBSL are useful for assessing the need for new water quality standards based on health risk and

evaluating the significance of ambient concentrations in natural waters (Toccalino & Norman, 2006).

Although more than 250 million Americans receive drinking water from public water systems, there remain 43 million individuals who obtain their drinking water from unregulated sources. These Americans are located predominately in rural areas and 98% of the drinking water from unregulated sources is supplied by groundwater wells (Kenny et al., 2009). Unregulated drinking water sources (UDWS) present a different set of water management and quality challenges than public water systems. For example, rural well owners are responsible for maintaining proper well stewardship to limit contamination; however, many people are unaware of these responsibilities and fail to maintain their drinking water infrastructure properly (CDC, 2006; Simpson, 2004).

Additionally, the primary legislative mechanism for evaluating and maintaining high quality drinking water in public water systems, the Safe Drinking Water Act, does not apply to UDWS. These water sources are generally privately owned by individuals and do not meet the definition of a public water system. As a result, these water sources are infrequently tested for contaminants, which presents a human health challenge due to unknown risk from water contaminants (Flanagan, Marvinney, Johnston, Yang, & Zheng, In Press; A. Q. Jones et al., 2006). Water quality testing and remediation become the responsibility of the well owner, and therefore, reflect important financial considerations. Water quality testing for trace metals and other contaminants may cost thousands of dollars, and the cost of drilling a new well or expanding a current well may be unaffordable to the owner (A. Q. Jones et al., 2006; Ryker, 2003). As a result of these challenges, additional research is needed to identify unregulated sources in the United

States, to evaluate the existing data about these sources and to better understand the accessibility of these data (Backer & Tosta, 2011).

There exist few national studies evaluating the quality of unregulated drinking water sources in the United States. Facazio et al (2006) assessed the quality of domestic groundwater wells for a range of chemicals including pesticides, volatile organic carbons, radionuclides and inorganic chemicals. The results of this study indicated that inorganic contaminants were regularly identified in domestic wells and that concentrations of these chemicals exceeded SDWA MCLs more frequently than organic chemicals. Arsenic for example, was detected in more than 50% of domestic well samples but exceeded the MCL in only 11% of samples (Focazio et al., 2006).

DeSimone et al. (2009) completed a more recent national evaluation of drinking water quality from unregulated sources in the United States. Data for this study were drawn from the National Water-Quality Assessment Program operated by the U.S. Geological Service. Water quality information from approximately 2,100 private water wells was evaluated for contaminants. The wells are representative of water quality conditions in the 62 major aquifers throughout the United States. Results indicated that one in five water samples from privately owned domestic wells contained at least one contaminant that exceeded HBSL. Radon, uranium, arsenic, manganese, strontium and nitrate were the most common contaminants to exceed established human health screening levels. Except for nitrate, these contaminants originated from natural sources. The authors of this study suggested that greater public education and water quality testing for private groundwater wells be initiated, due to the fact that many homeowners and

well users are unaware of groundwater contaminants such as arsenic (DeSimone et al., 2009).

Arsenic Occurrence

Arsenic is ubiquitous, though not abundant, in the global environment (Ng, Want, & Shraim, 2003) and is the 20th most common element in the Earth's crust (Buchet & Lison, 2000). In the natural environment inorganic arsenic exists in four oxidation states including arsenate (+V), arsenite (+III), arsenic (0) and arsine (-III) (Sharma & Sohn, 2009). In aqueous solutions, arsenic usually occurs as arsenate (H_3AsO_4 , H_2AsO_4^- , HAsO_4^{2-} or AsO_4^{3-}) and as arsenite (H_3AsO_3 , H_2AsO_3^-) in anoxic environments (Mondal, Majumder, & Mohanty, 2006). Arsenic (0) and arsine are uncommon in aqueous solutions.

In water, arsenic speciation is directly influenced by pH and the amount of dissolved oxygen in the system (Meacher et al., 2002). Arsenic mobilization from solid materials to aqueous solutions occurs in groundwater for a variety of reasons. For example, groundwater may experience oxygen infiltration, causing oxidation. The oxidation of iron oxide (arsenopyrite) is expressed as: $\text{FeAsS} + \frac{7}{2}\text{O}_2 + 4\text{H}_2\text{O} \rightarrow \text{Fe}(\text{OH})_3 + \text{H}_3\text{AsO}_4 + \text{H}_2\text{SO}_3$ (Welch, Westjohn, Helsel, & Wanty, 2000). Water and oxygen oxidize the arsenopyrite resulting in the formation of iron oxide, arsenate (As III) and sulfuric acid. The sulfuric acid is associated with acid mine drainage resulting in extremely low pH measurements and very high arsenic levels in groundwater. For example, groundwater at a California mine associated with a vein of arsenopyrite produced underground pH conditions of -3.6 and arsenic concentrations as high as 0.340 grams per liter (Nordstrom, Alpers, Ptacek, & Blowes, 2000).

The ubiquitous nature of arsenic in the earth's crust results in frequent natural contamination from geological sources (Buchet & Lison, 2000; Smedley & Kinniburgh, 2002). Arsenic contamination is also known to occur in closed basin environments in semi arid climates or in aquifers with strongly reducing conditions (Nordstrom, 2002). There exist documented cases of arsenic groundwater contamination associated with arsenic poisoning in countries such as Argentina (Hopenhayn-Rich et al., 1996), Bangladesh (Argos et al., 2010; Chowdhury et al., 2000; Smith, Lingas, & Rahman, 2000), India (Bhattacharjee, Chakravarty, Maity, Dureja, & Gupta, 2005), Pakistan (Nickson, McArthur, Shrestha, Kyaw-Myint, & Lowry, 2005), Taiwan (C.-J. Chen, Kuo, & Wu, 1988; Tseng et al., 1968), China (Xia & Liu, 2004), Mongolia (Hagiwara, Akai, Terasaki, Yoshimura, & Luo, 2011; Ning et al., 2007), and Chile (Caceres et al., 2005). There exist many reported examples of arsenic groundwater contamination in the United States (Focazio et al., 2000; Frey & Edwards, 1997), Hungary (Rowland et al., 2011), Finland (Kurtio, Pukkala, Kahelin, Auvinen, & Pekkanen, 1999), Peru (Vahter et al., 1995) and France (Mondal et al., 2006).

As discussed, rural private wells, including those in developed countries, rarely include water treatment for trace metals such as arsenic, putting people who obtain their daily drinking water from these untreated water sources at higher risk for arsenic exposure (Camacho et al., 2011). With regards to treatment, there are reported cases of people installing inadequate and ineffective filtration systems to remove arsenic, thereby creating a situation in which water consumers are aware of contamination yet are not appropriately protected (Flanagan et al., In Press; Walker, Shaw, & Benson, 2006).

Adults consume approximately 10 µg of inorganic arsenic daily and as much as 30% of inorganic arsenic exposure is attributed to drinking water (Abernathy, Thomas, & Calderon, 2003). In some cases drinking water may contribute as much as 100 µg of inorganic arsenic per day to the human body (Ulman, Gezer, Anal, Töre, & Kirca, 1998). After ingestion, inorganic arsenic is methylated into a less toxic form (Smith et al., 1992) and 45-85% is excreted from the body one to three days later (Caceres et al., 2005).

The remaining arsenic accumulates in the body potentially causing neuropathy, decreased IQ and memory issues, skin pigmentation issues, skin lesions, keratosis, hypertension and cancer of the skin, lungs, bladder and kidney (Buchet & Lison, 2000; Kapaj, Peterson, & Bahattacharya, 2006; Kavcar, Sofuoglu, & Sofuoglu, 2009). Inorganic arsenic exposure via drinking water is linked to elevated cancer rates in infants, children and adults (Meacher et al., 2002; National Research Council, 1999, 2001). The cancerous impact of arsenic contaminated drinking water is well documented. Some of the earliest evidence suggesting arsenic health effects from drinking water were demonstrated during the 1930s in Argentina (Smith, Lopipero, Bates, & Steinmaus, 2002). The United States Public Health Service formally recognized the deleterious health impacts of arsenic when it promulgated the first arsenic drinking water regulation for the United States in 1942. More recently in 2001, the US EPA reduced the SDWA arsenic MCL from 50 to 10 parts µg per liter to preserve public health (National Research Council, 2001; US EPA, 2001). According to the US EPA, the 2001 arsenic rule change affected 12-13 million people (Camacho et al., 2011). The US EPA estimated, that the lowered arsenic MCL would prevent 19-31 cases of bladder cancer, 5-8 bladder cancer

deaths and prevent 19-25 cases of lung cancer and 16-22 deaths from lung cancer annually in the United States.

The US EPA's recommendation to reduce the arsenic MCL from 50 to 10 µg per liter was based on relevant epidemiological studies and arsenic occurrence in the United States. Several national arsenic occurrence studies have been completed to identify areas in the United States most impacted by arsenic groundwater contamination. The earliest attempt to characterize arsenic exposure throughout the United States was the National Inorganic and Radionuclide Survey (NIRS). The objective of NIRS was to characterize the chemical makeup of community water systems supplied by groundwater. The study relied on a stratified random sample of 1,000 water systems throughout the country.

A comprehensive list of approximately 47,700 water systems was stratified by size into four categories: very small (25-500 people), small (501-3,300 people), medium (3,301-10,000 people) and large and very large (> 10,000 people). Sampling occurred between 1984 and 1986 and included water samples from 990 of the randomly selected systems (Longtin, 1988). While this study resulted in the characterization of community groundwater system water quality, it had several important design limitations. The study was limited in geographic scope and the analytical detection level of instruments was 1-5 µg per liter, which is too high for reliable characterization at low concentrations (Frey & Edwards, 1997). A subsequent study was completed in the 1990s to sample for arsenic and more accurately determine national occurrence levels.

The National Arsenic Occurrence Study (NAOS) built on NIRS results. The NAOS sampled drinking water supplies based on geographic location, water source type and system size. Surface and groundwater systems were sampled as well as large and

small systems. For the purposes of the NAOS study, a large public water supply system served more than 10,000 people and a small system served less than 10,000 people. Of the large systems that provided raw water samples for the study, 55% used surface water and 45% used groundwater. For the small systems, 30% used surface water and 70% used groundwater.

The survey results indicated that arsenic concentrations were higher in groundwater than surface water. Regionally, the lowest arsenic concentrations were detected in the southern and eastern portions of the United States and the highest arsenic concentrations were observed in the western United States. The authors determined that 25% of all community water systems had arsenic concentrations that exceeded 2 µg per liter, 6-17% of systems had arsenic concentrations greater than 5 µg per liter and 1-3% of systems had arsenic levels that exceeded 20 µg per liter (Frey & Edwards, 1997). While this study attempted to characterize national arsenic incidence, small systems (less than 1,000 people) were not well represented and the US EPA determined that the 5 µg per liter reporting limit for the NAOS was too high and limited the application of results (Focazio et al., 2000).

The US Geological Survey (USGS) completed an additional arsenic occurrence study using water quality information compiled from the National Water Information System (NWIS). These data included arsenic measurement from regulated sources and unregulated sources; unregulated water supplies were excluded from earlier occurrence studies. By using both regulated and unregulated water sources, the USGS was able to better characterize groundwater conditions throughout the United States (Figure 2). More than 18,000 groundwater arsenic observations were extracted from the NWIS and

analyzed. Approximately 12% (2,262 observations) of the samples were from public water systems and the remaining 88% (16,602 observations) were from unregulated water sources.

The median arsenic level of all water samples was less than 1 µg per liter, which indicated that arsenic contamination of groundwater was uncommon despite the ubiquitous occurrence of arsenic in the environment. For public water systems, 36% of samples had measured arsenic levels that exceed 1 µg per liter, 14% of systems had arsenic greater than 5 µg per liter, 8% of systems had arsenic greater than 10 µg per liter, and 1% of systems had arsenic that exceeded 50 µg per liter (Focazio et al., 2000).

Regionally, the highest groundwater arsenic concentrations were found in the western United States (Welch et al., 2000). Arsenic concentrations in shallow groundwater tend to be elevated in arid areas including locations in Oregon, Nevada, Utah and parts of California. For example, the shallow groundwater and reducing redox chemistry in Owens Lake, California results in very high levels of arsenic in groundwater (Ryu, Dahlgren, Gao, & Tanji, 2004; Ryu, Zierenberg, Dahlgren, & Gao, 2006). Geothermal water sources are also associated with elevated arsenic levels. A tributary of the Owens River has elevated arsenic concentrations due to geothermal activity mobilizing arsenic in the water (Hering & Chiu, 2000; Hudak, 2000; Kneebone, 2000; Levy, Schramke, Esposito, Erickson, & Moore, 1999).

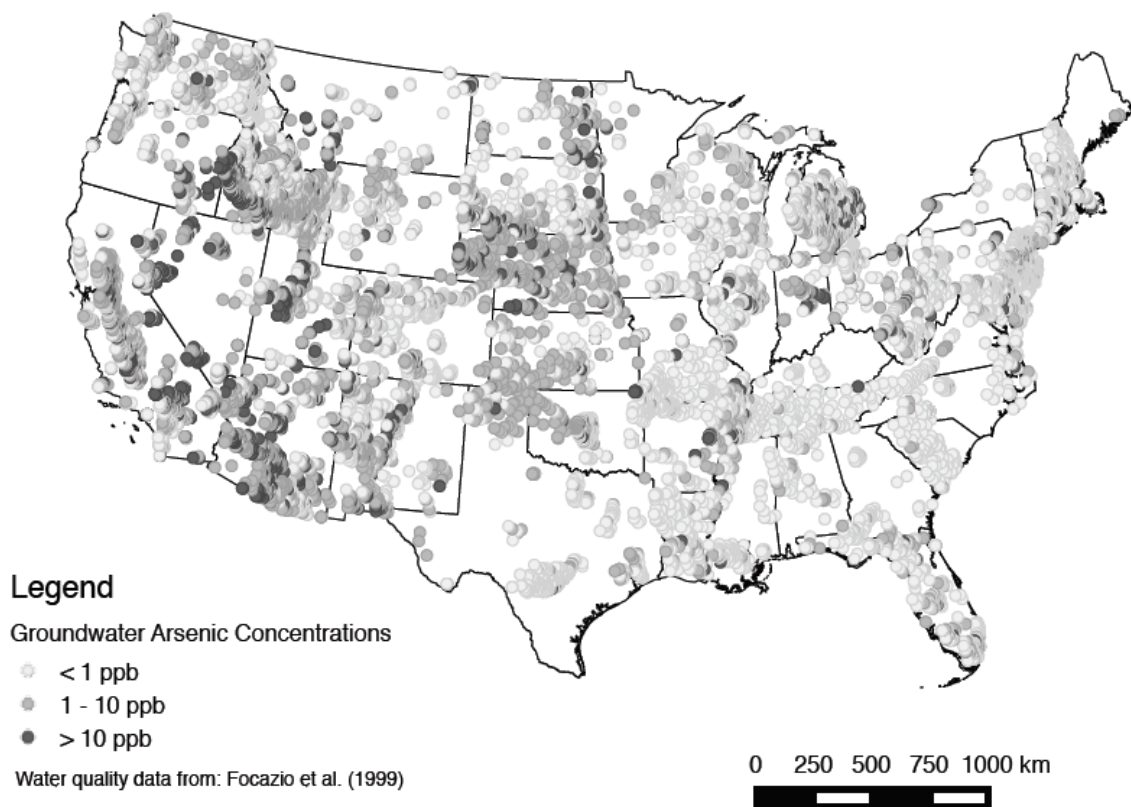


Figure 2: Illustration of arsenic groundwater contamination in the United States.

Elevated arsenic groundwater concentrations are also associated with volcanic rocks in South Dakota, Oregon and Arizona. In the southwest, localized arsenic studies have been conducted in California (Farrar, 1987; Gao, 2004; Guler, 2004; Mariner, 1976; Nordstrom et al., 2000; Ryu et al., 2006; Swain, 1993), Arizona (Camacho et al., 2011; Uhlman, 2008; Uhlman et al., 2009) and New Mexico (Athas, 2010; Chapin & Dunbar, 1994) and Nevada (Shaw, Walker, & Benson, 2005; Walker, Benson, & Shaw, 2005; Walker & Fosbury, 2009; Walker et al., 2006).

Arsenic is an important contaminant in the southwestern United States (Camacho et al., 2011) and some of the best documented US cases of arsenic water contamination

occur in Arizona (Smedley & Kinniburgh, 2002). In Arizona, arsenic is the most common naturally occurring water contaminant (Cory & Rahman, 2009; Uhlman et al., 2009) and many public water systems have sources with arsenic exceeding 10 µg per liter (Sofuoglu et al., 2003). Arsenic contamination is derived from natural sources including lake beds with fine material such as clay, aquifers with rocks of volcanic origin, geothermal environments or areas with gold and uranium deposits (Spencer, 2002). In Arizona, residents withdraw drinking water from more than 100,000 private domestic wells that are unregulated by the Safe Drinking Water Act. As a result, water quality for many of these wells is unknown and may be impaired. The Arizona Department of Environmental Quality (ADEQ) regularly conducts groundwater measurements in basins throughout the state testing for contaminants such as arsenic. Between 1995 and 2009, 17% of collected samples (229 out of 1,117 samples) exceeded the arsenic MCL. The ADEQ has completed groundwater basin studies for 29 of 51 basins in Arizona (Uhlman, 2008), though, to date, no basin in the Four Corners area has been studied in detail.

Arsenic contamination in excess of 10 µg per liter is common in the alluvial aquifers of central and southern Arizona. These aquifers consist of fine grain material that bind arsenic and oxidizing groundwater conditions cause the release of arsenic. For example, the Wilcox Basin in southeastern Arizona is known to have arsenic levels that exceed 10 µg per liter in groundwater (Vinson, McIntosh, Dwyer, & Vengosh, 2011). In central Arizona, groundwater in the Verde Valley experiences arsenic contamination including some locations with measured concentrations exceeding 500 µg per liter (Foust, Mohapatra, Compton-O'Brien, & Feifel, 2004).

At Montezuma Well for example, residents observed several cases of livestock animals delivering stillborn babies, which raised the suspicion of arsenic poisoning due to a nearby mine. Researchers measured arsenic concentrations in the local groundwater and observed levels between 10 and 48 μg per liter (Foust et al., 2004). Arsenic speciation suggested that the presence of a nearby mine did not impact arsenic levels in groundwater and that it was groundwater contact with the Supai and Verde Formations that caused elevated arsenic levels. Elevated groundwater arsenic is associated with the Supai Formation since arsenopyrite, an arsenic bearing mineral, precipitated in the formation. Eroded alluvial material from the Supai Formation formed the foundation of aquifers in the Verde Valley (Uhlman, 2008). The Supai Formation is also common in the Four Corners of northeast Arizona where Navajo Nation residents rely on aquifers for drinking water.

Outside of Arizona, dissolved arsenic levels create a public health concern in New Mexico, which receives more than half of its public water supply from groundwater. Geologically, New Mexico has a high percentage of igneous rock formations, which have previously been associated with elevated arsenic levels (Chapin & Dunbar, 1994) and the presence of igneous rock and geothermal activity causes elevated arsenic levels in groundwater (Smedley & Kinniburgh, 2002). In New Mexico more than 600 public water systems provide drinking water to 85% of the population and the remaining 15% received drinking water from private domestic wells. Approximately 80% of the state's population relies on groundwater for drinking water supply (Brandvold, 2001).

Between 1990 and 2005, the New Mexico Environmental Department measured dissolved arsenic concentrations at 2,200 sites throughout the state collecting more than

5,500 groundwater samples. Results indicated that measured arsenic concentrations ranged between 1-184 µg per liter and arsenic exceeded the SDWA MCL at 234 locations. Most locations that exceeded the arsenic MCL were located along the middle stretch of the Rio Grande River including Sante Fe and Socorro counties (Athas, 2010). Groundwater conditions in the middle Rio Grande include both oxidizing and reducing conditions. Near surface groundwater tends to be moderately oxidizing with low arsenic levels. These conditions occur due to shallow groundwater that is recharged by highly oxygenated river and irrigation water. Deeper groundwater in the middle Rio Grande is less hydraulically connected to surface water supplies resulting in higher water temperatures and pH leading to less oxidation (Chapin & Dunbar, 1994). Water chemistry results also indicated that 96 public water systems, that provide drinking water to 40% of the state, recorded dissolved arsenic concentrations exceeding 10 µg per liter (Athas, 2010; New Mexico Drinking Water Bureau, 2004).

Navajo Nation.

The Navajo Nation is comprised of 110 chapters, approximately 174,000 residents and is the only Indian tribe with authority from the United States federal government to implement a public water supervisory system (PWSS) program (Navajo Division of Health, 2013; Navajo Nation, 2014). Drinking water on the Navajo Nation is provided primarily by three sources: the C, N and D aquifers. The C aquifer is a multiple aquifer system that stores groundwater over an area larger than 27,000 square miles. The C aquifer extent generally conforms to the boundaries of the Little Colorado River Basin, though it does include portions of the Salt and Verde River watersheds. The C aquifer is primarily composed of the Kaibab Formation, Coconino Sandstone and the Upper Supai

Formation. The C aquifer is unconfined for most of its area with hydraulic connectivity between the Kaibab Formation, Coconino Sandstone and Upper Supai Formation. The C aquifer is named for the Coconino Sandstone, which is the primary water-bearing unit within the system, found continuously in the subsurface for almost the entire extent of the aquifer. Coconino Sandstone generally has a thickness ranging between 60 and 900 feet. Upper portions of the aquifer in the Kaibab Formation and Coconino Sandstone have good quality water, where as water in the Upper Supai Formation is degraded due to increased dissolved solids from the presence of evaporates (US BOR, 2006). Primary groundwater exports include surface discharge and downward leakage from the lower confines of the Upper Supai Formation to the Redwall-Muav aquifer. The Redwall-Muav aquifer is composed of limestone that is hydraulically connected to the C aquifer.

Human withdrawals in the form of groundwater pumping have increased since the 1940s. In 1940 it was estimated that approximately 5,000 AF of groundwater was pumped annually and by 1995 groundwater pumping increased to 140,000 AF annually. Population growth and agricultural development are the primary causes of increased aquifer pumping (Bills & Flynn, 2002; C. R. Brown & Macy, 2012; Hart, Ward, Bills, & Flynn, 2002).

The N aquifer is found laterally across 5,400 square miles in and around the Navajo and Hopi Reservations and holds an estimated 180 to 400 million AF of water (US BOR, 2009). The N aquifer is an important water source for the Black Mesa area and is composed of three formations that function as a single aquifer: Navajo Sandstone, Kayenta Formation and the Lukachukai Member of the Wingate Sandstone. The aquifer name is derived from the Navajo Sandstone component, which is the primary water

bearing unit (Macy, Brown, & Anderson, 2012). The N aquifer consists of a confined zone that underlies the Black Mesa and an unconfined zone that exists on the edges of the aquifer system. Recharge occurs where Navajo Sandstone is exposed near Shonto, Arizona. The N aquifer is an important municipal water source for the Navajo and Hopi residents as it has a total dissolved solids concentration of less than 500 milligrams per liter (Truini & Macy, 2006), and contains better water quality than the D aquifer which lies over the N aquifer. The average age of water¹ in the N aquifer is approximately 20,000 years and there may be some natural leakage between the N and D aquifers (Truini & Macy, 2006). The USGS has conducted water quality and quantity monitoring in the Black Mesa area since 1978.

Groundwater pumping from the N aquifer is linked directly to industrial use by Peabody Western Coal Company. Prior to the 1968 opening of the Kayenta mine in Black Mesa relatively little groundwater pumping occurred; however, the Kayenta mine relied on slurry line to transport coal to the Mojave Generating Station. Coal production peaked in 1982, which corresponds to peak industrial use of groundwater. In 2005 the Mojave Generating Station (MGS) was decommissioned due to environmental pressure and water supply restrictions. Peabody then reduced coal production and terminated the coal slurry line to MGS. As a result, total groundwater pumping from the N aquifer dropped from 5,000 AF in 2005 to 1,200 AF in 2006. Between 1,000 and 1,500 AF of groundwater is used annually for dust control by Peabody. Groundwater pumping for municipal use increased beginning in the 1950s due to population growth in Black Mesa.

¹ Age of water refers to the amount of time the water has been separated from the atmosphere. Age was determined using carbon isotope dating and measuring tritium concentrations (Truini & Longworth, 2003).

The D aquifer is the third important groundwater source for the NN and it lies above the N aquifer resulting in some leakage between the N and D aquifer units. Geologically, the D aquifer consists of Dakota Sandstone, Morrison Formation and the Carmel Formation, which are hydraulically connected. The D aquifer is named for Dakota Sandstone, which is the primary water-bearing unit. Water-rock reactions, due to weak acid and strong base conditions cause the dissolution of solids in the groundwater. As a result, groundwater in the D aquifer has a total dissolved solids concentration of more than 1,000 milligrams per liter, which exceeds the US EPA recommended level for drinking water. Mancos shale, which is relatively impermeable, lies over the D aquifer and creates a confined aquifer for much of its extent. Aquifer recharge occurs in areas where Mancos Shale is absent and the Dakota Sandstone is covered by unconsolidated material. Since much of the aquifer is confined, recharge is slow as indicated by the average age of water in the aquifer. Truini and Longworth (2003) determined that water remains in the D aquifer between 4,000 and 33,000 years.

Groundwater quality of drinking water sources on the NN is impacted by naturally occurring contaminants such as arsenic. According to 2010 consumer confidence reports from 90 Navajo Tribal Utility Authority (NTUA) water systems, 17 systems had measurable levels of arsenic and eight of these systems had arsenic levels that exceeded the MCL. Arsenic occurrence in groundwater presents a human health challenge due to the fact that a large number of NN residents acquire drinking water from unregulated sources (Leeper, 2003). With the exception of the Black Mesa, few areas on the NN have long term water quality measurements. In the 1970s, the Bureau of

Reclamation initiated a water-monitoring program in response to concerns regarding water use and quality impacts of the Peabody Western Coal Company Keyenta mine.

The first water chemistry characterization occurred in 1963 with follow up analyses conducted in 1978, 1982, 1983, 1985, 1986, 1988, 1989, 1992, 1993 and annually since 1995. Water chemistry in the area has been evaluated using samples from 21 groundwater wells in the area including 4 wells sampled annually and 17 additional wells sampled on a rotating basis. In 2011, the USGS sampled 11 groundwater wells and tested for contaminants including arsenic. Between 2001 and 2011, four of the sampled wells had arsenic levels that exceeded the MCL including two wells with an average arsenic concentration greater than 40 µg per liter. Thus far, the USGS has concluded that no trend exists for overall water quality decline or improvement in the area (Macy et al., 2012).

Additional groundwater sampling has been conducted in other areas of the NN including a widespread campaign in the 1990s and follow up work between 2001 and 2004. Between 1994 and 2000 the US EPA worked with the US Army Corps of Engineers (USACE) to assess the impact of historic uranium mining activity on groundwater quality. The USACE sampled 226 groundwater sources and analyzed for 23 metal and 11 radionuclide chemicals. The sampling was conducted at the collection point for each water source and the chemical analysis results were used to assess human health risks for each water source. Of the 226 groundwater wells, 35 locations (15%) had arsenic levels that exceeded 10 µg per liter with a maximum concentration of 282 µg per liter (US EPA, 2006). Between 2001 and 2004 a limited resampling campaign was conducted in the Hopi Buttes area of the NN. The U.S. Geological Survey collected 35

water samples from 18 groundwater sources. The results indicated that 10 of the 18 sample locations had arsenic levels that exceed 10 µg per liter with dissolved arsenic concentrations ranging from 1 to 180 µg per liter. Based on the results of these studies, 150 groundwater sources (61.2%) had arsenic levels exceeding 1 µg per liter, 83 groundwater sources (33.9%) had arsenic levels exceeding 5 µg per liter, and 38 sources (15.5%) had arsenic exceeding 10 µg per liter.

Other studies investigating water quality on the Navajo Nation reported arsenic levels in groundwater that regularly exceeded the SDWA MCL. In a study investigating water quality in five chapters near Churchrock, NM researchers reported that arsenic was frequently detected in unregulated drinking water sources (deLemos et al., 2009). A separate study investigated water quality for 11 chapters in the northern portion of the NN. Researchers evaluated water quality among 101 water quality samples from unregulated water wells and reported 27% of samples (n = 26) contained arsenic at levels that exceed the SDWA MCL (Fennema, 2013). Better access to existing environmental data for arsenic contamination in this area would raise issue awareness and potentially benefit resource users (deLemos et al., 2009).

Mechanisms For Informing Stakeholders

Two underlying research-based findings support the need for the current study:

- Awareness of groundwater contamination is a challenge for private domestic well users;
- A gap exists between known potential contaminants and awareness of those known contaminants by users (Hynds et al., 2013).

There currently exist several mechanisms for providing environmental information to decision-makers, stakeholders and the general public. One goal of

providing water quality information to rural, UDWS users is to increase issue awareness. Roche, Jones-Bitton, Majowicz, Pintar, and Allison (2013) surveyed private well owners in Newfoundland and Labrador, Canada to better understand the factors that affect how water quality information is disseminated. Results from this study indicated that only one-third of survey respondents recalled receiving information about drinking water contamination in their area. People who reported receiving water quality information most commonly stated that they obtained the information from a water treatment company, the local environmental department, health department or a real estate agent. The results of this study indicated that respondents were likely to acquire water quality results and information about water quality testing from flyers, brochures, television or radio advertisements (Roche et al., 2013).

These results are similar to another research study conducted with residents in Ontario, Canada, which found that nearly 47% of survey respondents indicated that it was “very important” that they receive more information on water quality testing, and 35% of respondents indicated that it was “very important” that they receive water quality information on other private wells near their own. Regarding access to this information, the results of this study indicated that resource users preferred to receive information from flyers or brochures mailed to their homes, with a low preference for using the Internet to disseminate water quality information (A. Q. Jones et al., 2006). This finding conflicts with other research that supports the use of the Internet as a source of environmental information (Bacic et al., 2006; Jankowski, 2009; Jankowski, Tsou, & Wright, 2007; Owen, Jankowski, Williams, & Wulforst, 2008).

Evidence suggests that provision of water quality results motivates private well owners to take action reducing contaminant exposure from drinking water. A study by Poe et al. (1998) determined that perceptions regarding the health impacts of nitrate groundwater contamination changed after receiving water quality test results, and that public information campaigns impact well users' perceptions of contaminated water risk. Flanagan et al. (In Press) reported that people who received information regarding the presence of arsenic in their drinking water were motivated to take actions that reduced their arsenic exposure via drinking water. Risk was found to be a motivating factor for reducing arsenic exposure through drinking water (Flanagan et al., In Press).

Access to water quality results does not guarantee a change in behavior, however. For example, some resource users may fail to understand the implications of the results. A. Q. Jones et al. (2006) reported that 20% of survey respondents did not know what water quality parameters were tested. Kreutzwiser et al. (2011) similarly reported that 17% of respondents did not know the water quality parameters tested, and failed to understand the test results or their implications for human health. In a study conducted in Churchill County, Nevada survey results indicated that citizens had a high level of awareness of arsenic groundwater contamination, yet 28% of respondents were unconcerned about the health impacts of consuming arsenic contaminated drinking water. Of the respondents who were unconcerned about arsenic contamination, 60% consumed water that exceeded 10 µg per liter (Walker et al., 2006).

Imgrund, Kreutzwiser, and de Loë (2011) reported that knowledge of water quality challenges was an important antecedent for private well owners' decision to test for contamination. Information itself was insufficient to change owner drinking water

consumption; however, it was found to lead to more water quality testing and better well stewardship. Other studies, however, investigating well owner testing behavior in Canada indicated that inconvenience, time constraints and financial concerns were the primary motivating factors for not testing well water for contaminants (A. Q. Jones et al., 2006; Kreutzwiser et al., 2011; Roche et al., 2013).

A summary article by Lucas, Cabral, and Colford (2011) evaluated the impact of information provision on well owner behavior. The studies reviewed by Lucas et al. emphasized changing well owner behavior through provision of water quality information. The authors reported on four studies in which provision of arsenic levels in drinking water from rural wells resulted in resource users switching to another well with lower arsenic levels. Results from several studies in Bangladesh indicated that consumers were likely to switch wells when presented with water quality information indicating elevated arsenic levels (Y. Chen et al., 2007; Hadi, 2003; Hanchett, Nahar, Van Agthoven, Geers, & Rezvi, 2002); however, the evidence suggesting that water quality information causes behavioral changes is anecdotal (Lucas et al., 2011). The lack of rigorous comparison methods among studies limits the generalizability of findings. In particular, future research is needed for assessing how water quality information is provided to resource users and the method of dissemination (Lucas et al., 2011). There exists no consensus regarding the impact of information provision on changing well owner behavior leading to better well stewardship and more frequent water testing. As a result, additional research is necessary to better understand tools for disseminating water quality information for private groundwater wells, and to evaluate the impact of water

quality information on private well owner behavior. One of these methods includes using geospatial technology to increase access to data and visualize information.

Internet GIS

Geographic information systems (GIS) are useful for environmental management due to visualization capabilities and the map interface helps the general public interact intuitively with environmental data (Haklay, 2003; Kelly & Tuxen, 2003; Loh & Rykiel, 1992). GIS technology facilitates understanding of environmental problems and the associated policy solutions. Visualization of environmental information is one method that helps stakeholders understand the information (Bacic et al., 2006).

Early work integrating GIS technology with environmental decision-making focused on one-way communication with stakeholders. Frequently, maps were used to present decision alternatives and were helpful since they provided a new vision for water management not achievable without map usage. Furthermore, it has been demonstrated that maps help stakeholders better understand how to improve the decision-making process by modeling and visualizing geographic aspects of phenomenon (Appleton & Lovett, 2005; Bacic et al., 2006). Bacic et al. (2006) used map products and satellite imagery to present stream pollution information to agriculture stakeholders. Results indicated that stakeholders could understand the map products and that the maps positively impacted communication between the information providers and the stakeholders resulting in improved remediation action. Another study used maps to convey water quality of unregulated drinking water sources to resource users (deLemos et al., 2009). This study emphasized communication of health risks due to uranium contamination of drinking water. Researchers designed printed maps to visualize

uranium contamination and human health risks for Churchrock, Arizona in the eastern part of the Navajo Nation. Individuals from local communities then evaluated the maps and reported that the cartographic products would be useful for educating citizens about water quality problems, possibly leading to behavior changes and seeking out new water sources (deLemos et al., 2009).

GIS technology has evolved from its original development on mainframe computers and now incorporates Internet as a method of access and dissemination. Contemporary geospatial research highlights the use of the Internet as an important portal for people to locate, access and visualize geographic information (Li, Xiong, & Ou, 2011). Internet GIS research is advancing user capabilities through increased access, while enhancing abilities to explore and visualize information through more powerful GIS analysis tools (Khan & Adnan, 2010). Internet GIS is particularly useful since it employs the distributed nature of the Internet to increase access to GIS tools through a user-friendly interface that positively impacts access to environmental data (Jankowski, 2009).

Despite positive reports regarding the use of Internet GIS for environmental education and management, there exist limited research investigating the use of geospatial technology for conveying water quality information to rural, groundwater users. Internet GIS research has demonstrated that this technology is user friendly and enables users to intuitively interact with environmental data. Internet GIS technology represents one tool capable of disseminating water quality information to well owners in an accessible and comprehensible manner. Additional research is necessary to

understand the benefits and challenges associated with using Internet GIS for raising issue awareness of water quality challenges for unregulated drinking water sources.

Summary

Water quality issues continue to challenge residents in the southwest United States who rely on unregulated groundwater supplies for drinking water. In areas such as the Navajo Nation, limited safe drinking water access and a dispersed rural population provide additional complications to clean and safe drinking water provision. Rural water resource users require increased access to comprehensive water quality information to raise issue awareness and make informed choices regarding water supply and arsenic exposure. Without access to critical water quality information water users may unknowingly consume dangerous levels of contaminants through their drinking water.

One approach to increase knowledge and awareness is through use of GIS and Internet based applications. The outreach and education efforts of ENGOS and IHEs that inform citizens about water quality issues may be enhanced through use of internet GIS; however, this hypothesis is not addressed in the current literature. As a result, a need exists to study the effects of Internet GIS on water quality data access and dissemination for rural, groundwater users. Specifically, there exists a need to evaluate how effectively an Internet GIS disseminates groundwater quality information and to evaluate the perspectives of university academics and environmental nongovernmental organizations regarding using this technology to convey information to their stakeholders.

Chapter Three: The Value of Internet GIS For Disseminating Unregulated Drinking Water Source Quality Information

Introduction

The contents of this chapter describe the value of an Internet GIS for improving access to UDWS information and water quality test results. I hypothesize that Internet GIS technology will reduce the knowledge gap that exists between what is known about the quality of UDWS, and information that resource users know about drinking water from these sources. Ultimately, this technology may help raise issue awareness about groundwater contamination for unregulated sources, leading to changes in how UDWS consumers behave and perceive of health consequences due to contaminant exposure. To demonstrate the potential, I present in this chapter a description of an Internet GIS application designed to disseminate water quality information for UDWS on the Navajo Indian Reservation in the southwest United States.

Background

Throughout the United States, approximately 43 million Americans obtain drinking water from unregulated sources that are not subject to the water quality testing requirements of the Safe Drinking Water Act (Kenny et al., 2009). As a result, well owners infrequently test the quality of their drinking water; possibly consuming water with elevated levels of contaminants known to have deleterious human health impacts (Backer & Tosta, 2011). One in five unregulated sources provides drinking water that

commonly includes arsenic, uranium, nitrate or microorganisms at levels that exceed human health benchmarks (DeSimone et al., 2009). Due to these types of contaminants, a need exists to better understand unregulated drinking water source (UDWS) frequency of use and quality (Backer & Tosta, 2011). Research aimed at understanding well owner water quality testing behavior has demonstrated a need to increase access to environmental data as well as better disseminate water quality information to private well owners (Charrois, 2010; Roche et al., 2013). Geospatial technology is one tool capable of increasing access to water quality data for UDWS. However, limited research has applied this tool in the dissemination of water quality information for unregulated drinking water sources (deLemos et al., 2009).

Geospatial technology, maps and Internet-based applications have many benefits that will help disseminate existing water quality information for unregulated sources and potentially effect how private well owners view human health risk from contaminated groundwater. Dynamic visualization of environmental data, using geographic information systems (GIS) technology, has been applied previously to water resource management challenges (Choi, Engel, & Farnsworth, 2005; Dymond, Regmi, Lohani, & Dietz, 2004; Saltenberger, 2011), water quality monitoring (Elder, 2013; Jankowski et al., 2007) and water resources data access and management (Horsburgh, Tarboton, Maidment, & Zaslavsky, 2008; Horsburgh et al., 2009). However, there is limited research applying this tool for the dissemination of water quality information for UDWS. In particular, an Internet GIS application could enable UDWS users to access and view water quality information in a dynamic, user-friendly environment. The ease of use and visualization capabilities of an Internet GIS enables users to intuitively interact with

environmental data (Kelly & Tuxen, 2003). Since resource users experience difficulty interpreting water quality test results (Kreutzwiser et al., 2011), Internet GIS applications may alleviate this problem by presenting water quality information in a comprehensible manner accessible to the general public.

Unregulated Drinking Water Source Data Needs

Unregulated water sources provide daily drinking water to millions of Americans; however, the Safe Drinking Water Act does not regulate these water sources since they are not classified as public water systems. As a result, there is no legal mechanism mandating well owners to test for contaminants. Nearly all unregulated drinking water sources (UDWS) in the United States are groundwater wells, which are susceptible to contamination from microorganisms and chemicals. Previous work addressing resource consumer behavior and the needs of public health officials regarding UDWS has identified several research needs:

- Improve access to existing water quality information (Flanagan et al., In Press);
- Visualize and present water quality information to the general public (Backer & Tosta, 2011);
- Better communicate health risks associated with groundwater contamination (Roche et al., 2013);
- Present water quality information in a user friendly manner that the general public is able to understand (Hynds et al., 2013; Kreutzwiser et al., 2011);

- Assess the impact of water quality information on well owner water quality testing behavior (A. Q. Jones et al., 2006; Roche et al., 2013); and,
- Evaluate and design new tools and methods to disseminate water quality information to resource users and decision makers (Lucas et al., 2011).

Previous education efforts have focused on disseminating water quality information for UDWS using flyers, brochures, television and radio advertisements, and focus group discussions regarding water quality and health impacts (Brooke, 1996; Y. Chen et al., 2007; Hanchett et al., 2002; A. Q. Jones et al., 2006; Kreutzwiser et al., 2011; Roche et al., 2013). Few projects have investigated the ability of geospatial products, such as maps, to convey water quality and risk information to resource users (deLemos et al., 2009). Internet GIS technology is one tool that has the capacity to meet stated research needs for UDWS challenges including increasing access to existing water quality information, visualization of water quality data and presentation of water quality test results in a manner understandable to the general public. There exists much opportunity to apply Internet GIS in the study of UDWS information dissemination, impact and evaluation of rural, groundwater quality.

Internet GIS

The history of Internet GIS is linked to Internet mapping, which is developed in five distinct stages differentiated by technology developments and level of user interactivity. Understanding these development stages is critical for comprehending the

current status of Internet GIS technology and its capacity for addressing UDWS challenges.

The first generation of Internet mapping consisted of a static map embedded as an image file or link in a web page. Initially, digital maps were scanned copies of printed maps; however, researchers recognized that scanning a printed map document and posting it as an image for electronic access via the world wide web resulted in an inferior product. Maps needed to be designed specifically for dissemination via the Internet (Harrower, Keller, & Hocking, 1997). Research also addressed issues of low user interactivity, a restricted user interface, low graphics quality, and slow response time, resulting in the incorporation of cartography principles and geovisualization techniques into new dynamic map applications (Andrienko, Andrienko, Voss, & Carter, 1999; Peng & Nebert, 1997; Wright, O'Dea, Cushing, Cuny, & Toomey, 2003).

The second generation of Internet mapping, known as interactive web mapping, built upon the single click, stateless nature of the first generation by incorporating dynamic HTML (DHTML), Java applets and Active X plugins. DHTML is responsive to user page activity and has advantages over stateless HTML since it is reactive and the response is immediate (Peng & Tsou, 2003). An interactive web map was embedded in an HTML document allowing the user to zoom, pan, identify objects and click links to access additional information. The map was updated in real time based on user requests (Doyle, Dodge, & Smith, 1998). ESRI ArcIMS is the most well known example of a second-generation Internet mapping technology, for which many water resource and water quality examples exist.

For example, Pandey, Gunn, Lim, Engel, and Harbor (2000) developed a prototype system that used ArcIMS to model long-term hydrologic impacts of land use change. Dymond et al. (2004) created an Internet GIS to provide spatial decision support that integrated hydrologic modeling with economic and fish health models for a watershed in southwestern Virginia. The authors concluded that this type of system would be useful for engaging with citizens, nongovernmental organizations and planners. Similarly, Choi et al. (2005) created an application that combined two web services to create watershed boundaries and evaluate water quality. The authors stated that the system would be useful for watershed decision-makers and for people who needed to access and use hydrologic models. Other researchers have used ArcIMS to display river water quality (Wang, Homer, Dyer, White-Hull, & Du, 2005) and to manage sediment yield for the USDA's conservation reserve program (Rao et al., 2007).

Software such as ESRI's ArcIMS increased the interactive capabilities of Internet GIS and enabled the user to access analytical tools provided by a spatial server. This technology enabled the user to select a geographic feature and draw upon more information from the map server. There were, however, drawbacks associated with using this system architecture as an interface to access dynamic maps and models. For example high traffic volume between the client and server resulted in long response times and a need to regularly update custom plugins and applets (Huang & Worboys, 2001).

The transition to Internet mapping's third generation was marked by greater public awareness of geovisualization products and development of improved user interfaces. For example, news outlets used Google Earth to visualize the impact of Hurricane Katrina on New Orleans, Louisiana. Media use of Google Earth introduced

the general public to the visualization capabilities of Internet mapping applications and increased user numbers. In 2005, Google Maps was deployed using Ajax, which combined Asynchronous JavaScript, HTML, Document Object Model (DOM), eXtensible Markup Language (XML) and Cascading Style Sheets (CSS). Ajax is the combination of several existing technologies combined in a novel way enabling asynchronous server communication (Kuuskeri & Mikkonen, 2009).

The Ajax framework relies on an engine located between the browser and the server that loads in the background and controls the flow of client requests to and from the server. When the server receives a request and returns the result, the Ajax engine transmits information sufficient to fulfill the request and hold the remaining information in reserve for future requests. This process reduces response time and creates a more seamless application since server requests are limited (Chow, 2008). Continuous, asynchronous communication via small data packets improved interactivity, speed and interface usability (Peterson, 2012).

Ajax also contributed to the development of rich Internet applications (Tsou, 2011), which are graphically robust applications that combine the distributive nature of the Internet with desktop interactivity and functionality (Kay, 2009). Rich Internet applications (RIAs) have fast response and real time interaction, similar to desktop applications. These applications also reflect the cross platform compatibility, rapid deployment and efficient loading of distributive Internet services (Strode, 2012). There exist multiple types of RIAs including web browser scripting and plugins, web browser extensions and downloadable applications that display material outside of an HTML browser environment. JavaScript is the most common scripting RIA implementation

style where it is embedded in a HTML document and the code is read by the browser software. JavaScript is the only scripting language that can be read natively by all major browsers requiring no plugin installation (Kuuskeri & Mikkonen, 2009).

RIAs enabled a wider variety of user controls, such as drag and drop or map panning capability that enhanced the user experience. Partial page loading and client side storage increased application efficiency, decreased wait time, decreased bandwidth usage and shifted some of the processing work from the server to the client (Zhong, Jiang, & Hu, 2012). While RIAs enhanced Internet browsing, application performance varied and was highly dependent on the web browser (Hoetzlein, 2012). The number of online map users increased significantly due to deployment of sites such as Google Maps (Butler, 2006; Tsou, 2005), one of the best known RIA examples. Furthermore, release of the Google Maps application programming interface (API) resulted in widespread adoption and use of mapping web services for Internet applications. APIs consist of preformatted code that a programmer calls using JavaScript, php, or other scripting language (Hu, 2012); a web service is a set of rules that enables machine-to-machine communication over the Internet (Goodall, Horsburgh, Whiteaker, Maidment, & Zaslavsky, 2008) and a mashup is the combination of two or more web services.

APIs facilitate the creation of novel web-based GIS applications (Frew & Dozier, 2012). The preformatted code is accessible using representational state transfer (REST), which is a combination of Internet protocol, host and application pathways that link users to resources on a server (Battle & Benson, 2008). Accessing a REST end point is as simple as opening a standard web page (Avilés-López & García-Macías, 2012). APIs enabled web developers to better integrate web mapping services into applications, which

resulted in widespread adoption of geospatial data and services (C. E. Jones & Weber, 2012).

The fourth generation of Internet mapping is characterized by emerging data display methods, new interaction technology and the rise of novel geographic data collection methods (Plewe, 2007). The emergence of volunteered geographic information (VGI) and citizen science coincides with the development of the Web 2.0 framework that breaks down the barriers between experts and non-experts. Web 2.0 applications are designed to be participatory and encourage bidirectional communication.

According to Tsou (2011), we are currently in the fifth generation of Internet mapping, which is oriented towards cloud computing. Cloud computing provides computing as a service (Yang, Rasking, Goodchild, & Gahegan, 2010) and includes (a) infrastructure as a service, (b) platform as a service, (c) software as a service, and (d) data as a service (Mell & Grance, 2011). Cloud computing is an on demand service that consists of network access, pooled computing resources, rapid elasticity and is a measured service. Cloud computing is an economically viable way to develop and maintain a webmap for environmentally related subjects including a high performance site designed to publish large-scale species range maps (Zhang, 2012).

The progression through each generation of internet mapping illustrates that Internet GIS has progressed from a stateless, static map to a dynamic map interface that includes real time analytical processing tools using resources from multiple web services mashed together in a dynamic cloud-based application. Interface and tool developments have established frameworks useful for the visualization, dissemination and analysis of environmental data through a web interface. In particular, application programming

interfaces, rich Internet applications, REST and cloud computing are crucial for the adoption of powerful Internet GIS applications (Peterson, 2012). The storage and dissemination of environmental data benefits from these technologies, resulting in applications possessing much potential for positively impacting the study of unregulated water sources due to its visualization, accessibility and analysis capabilities of geospatial technology.

Internet GIS for UDWS.

GIS experts and novices alike now commonly use the Internet to locate, access and visualize scientific and geographic information (Butler, 2006). An online mapping application with a simple interface can be employed intuitively without training, assisting viewers to grasp environmental data (Kelly & Tuxen, 2003). Internet GIS applications have low user incurred costs since they are free to access, easy to use, require no specialized software to view information and are responsive to user requests (Harrower, 2004; Peterson, 2012). Internet GIS applications have many benefits that are advantageous for disseminating UDWS water quality information. This technology is easy to access via the Internet and does not require installation of customized software. The customizability of web services and available APIs enables developers to create web applications specific to UDWS challenges.

The map interface design is a critical element of a successful Internet GIS since it is how the end user interacts with the provided tools and environmental data. General guidelines regarding the basic structure of an Internet GIS are available in published literature (Table 1). An effective Internet GIS application uses a clear and simple layout with consistent menus and limited options to reduce user error (Nivala, Brewster, &

Sarjakoski, 2008). Online map users expect Internet maps to contain click events to view attribute information about map features (Komarkova, Novak, Bilkova, Visek, & Valenta, 2007; Krammers, 2008). This function enables the map designer to provide detailed information to users without cluttering the interface, guiding users to view metadata about map features (Leitner & Battenfield, 2000). Online map users also expect to re-center the map dynamically, to change map scale and view greater detail for specific areas (Harrower & Sheesley, 2005). The map size should be as large as possible on the webpage to maximize viewing area while minimizing the page space filled by non-map features (Harrower & Sheesley, 2005).

Previous research regarding dynamic map legend design has indicated that map icons, on their own, may be confusing and that a legend combining a textual description with the map icon effectively communicates the meaning of each map feature (Krammers, 2008). Furthermore, layer control, while useful for people with GIS training, has proven challenging for untrained GIS users. As a result, published literature suggests that map layer controls be disabled for novice users, and that the map designer use scale dependent rendering to provide greater map detail without cluttering the interface (Nivala et al., 2008). Although plugin-based applications have powerful visualization and analytical capabilities, users need to maintain the most current version of the plugin to access the application. Researchers have suggested use of scripts, such as JavaScript, for the deployment of Internet GIS applications to maximize the number of users who are able to access the GIS using common web browsers (Komarkova et al., 2007).

Table 1: A survey of existing Internet GIS design guidelines.

Design Aspect	Comments
Menus and sub-menus	Should remain concise and consistent throughout the site. Limited commands can reduce user error.
Feature identification	Clicking on an object to view attribute information if useful and expected by users.
Layer control	Non-expert users rarely utilize advanced functionality including changing layers.
Panning	Panning is the ability to re-center or reposition the focus on the map on screen and is a necessary companion to zooming.
Zooming	Zooming is most effective when map landmarks are used. The landmarks should be repetitive and appropriate for the users and the scale.
Legend	Users prefer an icon with associated text to help reduce ambiguity.
Map caching	Tiled maps improve page performance and decrease loading time.
Metadata	Important so that users can assess the validity and timeliness of information. Accuracy and detection limits are useful for understanding data limitations.
Map size	Maximize screen area of map and minimize advertisements and non-map areas.
Color	Carefully choose color scheme so as to not confuse the map user.
Page layout	Simple home page and consistent layout.
Software plugins	Try to avoid plugins to maximize accessibility and avoid losing participants to out of date software. Plugins do provide more powerful analytical and visualize capabilities however.

A gap in information access is one of the challenges confronting UDWS users. This knowledge gap impacts perceptions of human health risk due to groundwater contamination, frequency of water quality testing and well owner behavior. Additional

tools and methods are needed to address these challenges, with Internet GIS being one tool well suited to increase access to UDWS water quality information in a manner that the general public understands.

Internet GIS UDWS Example

To illustrate the value of an Internet GIS for UDWS water quality information dissemination, I applied the aforementioned design principles (Table 1) and created an Internet GIS application that illustrated arsenic contamination of UDWS throughout the Navajo Indian Reservation in the southwest United States. I adapted the development process for the Internet GIS from a user centered design framework proposed by Tsou and Curran (2008) that included: (1) determining the overall strategy and spatial database design for the Internet GIS, (2) creating an implementation strategy, (3) selecting a web map server and designing the map browser, and (4) evaluating the interface. The purpose for designing and using the developed Internet GIS was to determine the extent NGO staff and university researchers saw the value of such a website to inform their stakeholders of a water quality issue.

Internet GIS goals, strategy and database design.

Recognizing the challenges of accessing existing water quality information for unregulated wells throughout the study area, the goals of this Internet GIS were to (a) visualize existing arsenic measurements for unregulated groundwater wells and (b) illustrate access to water hauling stations. The mapping goals for the Internet GIS included provision of a dynamic and interactive map accessible through an Internet browser that used web services to visualize existing quantitative water quality information and safe drinking water access to water hauling stations.

After defining the user needs and mapping goals, I designed the spatial database for the project and produced a detailed list of data objects. To access information about water quality and water hauling stations, users needed the ability to change map scale, re-center the map, display multiple data layers simultaneously and access instructional materials to employ the map tools and terminology. Spatially referenced water quality information and the locations of water hauling stations were the most important data used in this prototype. The remaining information included base map features that provided geographic markers to orient users as they employed the Internet GIS (Gudes, Yigitcanlar, Tal, & Bar-Lavi, 2009). I identified a number of geospatial data layers necessary for the mapping application including (a) unregulated drinking water sources tested for arsenic occurrence, (b) water hauling stations, (c) public water systems, (d) local roads, (e) highways, (f) populated places, (g) residential structures within one mile of a uranium mine, (h) Chapter boundaries², and (i) the Navajo Nation (NN) boundary.

The attribute information for unregulated drinking water sources included measured dissolved arsenic concentrations (μg per liter) for 239 locations, available as ESRI shapefiles from previous US EPA and US Geological Survey studies (US EPA, 2000). Additionally, the NN EPA provided location (latitude and longitude coordinates) and attribute information for 67 water hauling stations. I also created a point data layer to represent locations of existing public water systems on the Navajo Nation. Using the Enforcement and Compliance History Online (ECHO) database from US EPA, I compiled a list of all active public water systems on the NN and matched the system names with known populated places.

² A chapter is a political sub-unit of the Navajo Nation tribal government that addresses the local land and health issues important to the chapter population (Navajo Division of Health, 2013).

Table 2: Summary of Internet GIS mapping features, functions and tools.

Function	Description
Feature identification	Used to call an information window with attribute information about unregulated wells, public water systems, towns, water hauling locations and buildings.
Zoom and pan	Zooming enabled the user to change the map scale and panning allowed the user to re-center the map.
Reset map extent	Located on the main map page, this button reset the map to its original extent. A second button was located with the spatial analysis tool to remove the tool results and reset to the original map scale.
Navigation and scale	Zoom in and out arrows were included in the map frame along with a scale bar set to English units.
Timer	A JavaScript enabled timer was used so that the participant would know how long he used the Internet GIS.
Dynamic layer rendering	Data layers were set with scale dependencies so that the map interface would not appear cluttered at small scales.
Instruction pane	A collapsible window was placed in the map frame with suggestions for getting started with the GIS application.
Arsenic gauge	This widget visualized contamination levels (μg per liter) using a dynamic gauge that was linked with unregulated wells and a hover over event handler.
Dynamic map legend	The dynamic legend illustrated the icon and textual description of all features currently visible in the map frame. The legend content updated as the user changed map scale.
Spatial analysis tool	A geoprocessing service activated by a click event that used a road network layer to create three driving distance service areas (5, 14 and 25 miles) and then executed an intersect by location to identify all water hauling stations in the service area. The map extent was set to 1.5 times the driving buffer extent.
Index	This pane included water resources and GIS terms and definitions.

ECHO indicated 176 public water systems on the NN, which is comparable to NN Department of Water Resource records. I successfully geocoded 121 systems and created a shapefile with these locations. I was unable to identify the locations for the remaining 55 public water systems, since these systems listed PO box addresses making it not possible to determine the actual service area of these systems. The public water system layer that I created using the ECHO database was intended as a proxy for proximity to an existing public water system. The remaining basemap data were available as shapefiles from previous US EPA studies.

I created a file geodatabase with defined relationships among the data layers and used the WGS 1984 geographic coordinate system and Web Mercator Auxiliary Sphere projection. This projection was selected so that the published map services were compatible with an existing topography web mapping service selected for use in the online application.

Map implementation strategy.

I included click identification tools, navigation tools for resetting the map extent, a dynamic map legend, a spatial analysis tool, a gauge widget that illustrated arsenic contamination in parts per billion, a collapsible instructions panel for the GIS application and an index with definitions for all GIS and water resources terms (Table 2).

Web browser design.

I used ArcGIS Server 10.1 deployed on Amazon Elastic Cloud Computing (EC2) to publish a web mapping service and geoprocessing service. All web services were deployed using an Amazon Machine Instance that included 3.75 GB of memory, 2 EC2 computing units, and Windows Server 2008. I used cloud computing for the deployment

of web services since it is an economically viable way to develop and maintain a webmap for environmentally related subjects (Zhang, 2012). Also, it was easily scalable, configurable (Mell & Grance, 2011) and reduced the need for local server infrastructure (Tsou, 2011). Using the ESRI JavaScript API, I accessed the published map service and geoprocessing service using their REST end points.

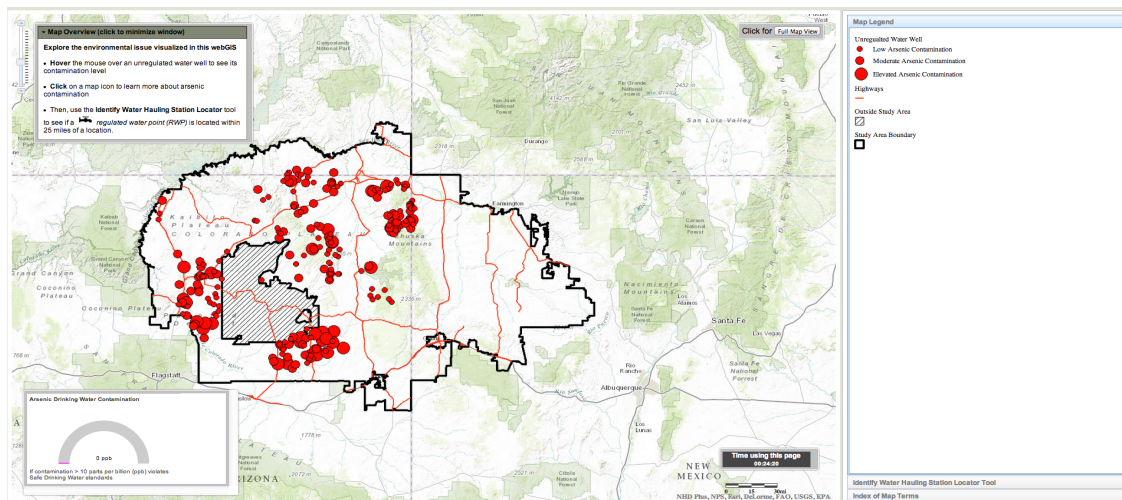


Figure 3: A screen shot of the GIS application user interface.

The GIS application was a single webpage with a map frame that occupied most of the page, collapsible instructions window, a gauge widget that illustrated arsenic contamination (μg per liter) and three accordion panes on the right side of the map window (Figure 3). These panes included a dynamic map legend, spatial analysis tool to illustrate safe drinking water access and an index of water resources and GIS terms used in the application. I also created a companion website that included background information on water quality issues in the study area and details regarding the Internet

GIS. After designing the GIS application, I evaluated it with three methods to improve the interface design for members from the study population.

Evaluation.

Pretesting with individuals of the intended population is a critical component of designing and deploying an effective Internet application (Newman et al., 2010). After designing a prototype Internet GIS, I evaluated the site with (1) a usability focus group, (2) expert review of the groundwater information, and (3) a pilot test of the GIS application. The goal for using these evaluation methods was to refine the prototype so that participants could focus on learning about the groundwater issue and reduce the burden associated with using a new user interface.

Usability focus group.

I recruited a small group of ENGO and IHE professionals to participate in a focus group evaluation of the Internet GIS. I used this method to identify potential usability problems with the prototype design. Usability is defined as the “extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context” (International Organization for Standardization, 1998, p. 2). Usability issues are design problems that diminish the effectiveness, efficiency or satisfaction of users in regards to the product. Two IHE and two ENGO professionals were recruited to participate in the focus group.

I asked each participant to complete five tasks designed to assess various aspects of the GIS application and to discuss his thought process for completing each task. The first, second and third usability tasks asked participants to locate, using the website, contact information, details about public water systems and the occurrence of arsenic on

the Navajo Nation. These tasks enabled me to assess page layout, font size, figure captions and how users move between pages. The fourth and fifth tasks were completed using the Internet GIS and necessitated use of multiple GIS functions to complete successfully. The fourth task was designed to assess the layout of the Internet GIS and the functionality of the find, zoom and identify tools included with the application. The fifth task required the participant to use and interpret a spatial analysis tool designed to visualize access to water hauling stations.

In total, the focus group participants identified 55 usability problems including 41 unique issues. There were 14 identified map usability problems that included concerns about map rendering after a scale change, symbol choice for groundwater wells and questions about the service area calculated by the spatial analysis tool. Participants also identified 18 issues associated with the map layout including the size of the scale bar, the title of the spatial analysis tool, the absence of instructions stating that users could click on map features to access attribute information, and limited information explaining the map symbols. There were also 22 issues associated with the website content including the source and fate of arsenic in the environment, the size of images on the website, font size, typeface and color. After completing the focus group, I made adjustments to the GIS application and then conducted the second evaluation step: expert review of the visualized water quality information.

Expert review.

I contacted eight water resource professionals knowledgeable in the domain of Navajo Nation groundwater contamination and asked each individual to evaluate the content of the website and Internet GIS. Using published reports on NN drinking water

quality challenges, I recruited area experts from US EPA, NN EPA, and Indian Health Service agencies. Expert review of geospatial content has previously been used in the development and evaluation of water resource GIS applications and is useful for identifying content inaccuracies and ambiguities (Slocum, Cliburn, Feddema, & Miller, 2003). I contacted each expert via email and asked if he or she would review the site. The email contained information about the purpose of the site, the overall research goals and the reasons for contacting the individual. I asked each person for his or her professional, expert opinion on the appropriateness of the presented information for representing arsenic groundwater contamination throughout the NN. I also asked the reviewers to use and evaluate the spatial analysis tool.

Three of the eight reviewers provided comments about the website and GIS. Although I asked the reviewers to assess content validity, several comments addressed site usability. In the initial prototype design, I used green, yellow and red circles to indicate level of arsenic contamination for unregulated drinking water sources. Several reviewers commented that the use of these colors, especially green and yellow, might suggest that it was safe to consume water from these unregulated sources and not encourage people to collect drinking water from water hauling stations. This is counter to the policy of the NN EPA that emphasizes avoiding consumption of drinking water from unregulated sources. Microorganisms and other chemical contaminants not visualized in the present study play a significant role in the safety of drinking water from these sources.

The reviewers thought the website and GIS material accurately represented arsenic groundwater contamination for the study area. Two reviewers also stated that

more recent, though limited water quality data existed; however, these data were not publically available and the reviewers concluded that the absence of this information did not negatively impact validity. After receiving and evaluating reviewer comments (18 in total), I made adjustments to the GIS prototype and then conducted the final evaluation step: pilot test with members of the study population.

Pilot test.

Following the focus group and expert review, I invited individuals from the target population to participate in a pilot test. I selected a stratified random sample of 28 individuals (50% IHE and 50% ENGO) from a compiled list of 205 potential study participants located in the western United States. The invited participants included water managers, program managers, GIS developers, university faculty and a state water extension specialist.

The pilot test was designed to evaluate if participants contacted via email could open the site, navigate to the GIS application and use it as intended. The second goal was to evaluate if participants who used the site could locate the survey link on the GIS application page and complete an online survey. Each participant was individually contacted via email and asked to participate. The invitation included a brief description of the project and GIS, the purpose of the study and a URL for accessing the study website. The survey was created and implemented using LimeSurvey, which is an online software useful for the development and deployment of survey tools. The survey questions included:

1. How much time did you spend using the webGIS applications?
2. With what type of organization are your primarily affiliated?

3. How much experience do you have using geographic information systems?
4. How much experience do you have using web-based GIS applications?
5. How comfortable are you using the Internet?
6. Do you have prior knowledge of water quality issues in the study area?

Follow up emails were sent two and four weeks after initial contact. I used Google Analytics to monitor the number of unique visitors, geographic locations of visitors (state level) and session length. Google Analytics is a free analytics software hosted by Google that has previously been used to monitor Internet GIS use in other environmental studies (Werts, Mikhailova, Post, & Sharp, 2012).

In total, Google Analytics recorded 22 site sessions between March 4 and April 9, 2013. For quality control purposes, only direct sessions that started from the homepage were included for analysis. A direct visit is recorded when a visitor opens a link connecting directly to the site rather than accessing the site through a search engine or other pathway; analytics recorded several site visits from unknown visitors during the pilot test period but none of these indirect visits included a GIS page view. Site sessions originated from five western US states including Arizona, California, Colorado, Idaho and Nevada and from individuals known to be abroad at the time email invitations were received. Each participant who used the GIS application completed the survey (n=13).

I asked pilot test participants to give general feedback about the GIS and website. Seven respondents provided comments including one person stating that the GIS application worked well. Another respondent stated that some of the language used on the site and GIS was unfamiliar and needed additional explanation; however, this person

did not indicate what terms were unclear. I received several comments that the map icons representing public water systems and identified water hauling stations (from the spatial analysis tool) were similar and therefore confusing. The remaining comments pertained to cosmetic issues including page layout, font size and spacing and the processing speed of the spatial analysis tool.

Design and evaluation summary.

The design and evaluation framework I employed for this Internet GIS enabled me to create an application that visualized unregulated drinking water source water quality for the Navajo Nation. The GIS is a rich Internet application that relies on cloud computing and web services accessed via their REST endpoints. The step-by-step process facilitated a thoroughly designed GIS and the three evaluation methods, enabled me to identify and resolve potential problems the users might encounter while accessing the application. The Internet GIS application presented in this chapter is a user-friendly tool that enables access to water quality information for unregulated water sources. This is one example of how an Internet GIS tool may be implemented to provide access to UDWS water quality information, visualize the information in a spatially explicitly context and present water quality results in a manner understandable by the general public. This chapter is limited to the design and evaluation of the tool for use. Chapter 4 summarizes findings regarding ENGO and IHE professionals' perceptions about the capacity of this tool for conveying water quality information and helping users learn about groundwater contamination of unregulated sources on the Navajo Nation.

Conclusion

Internet GIS technology impacts environmental data access, issue awareness and participation in environmental decision-making (Argent, 2004; Desai et al., 2009). The GIS application presented in this chapter illustrated the potential benefits of Internet-based geospatial technology for the distribution and visualization of water quality information for unregulated drinking water sources. The design process and use of individuals from various backgrounds and experiences improved site terminology, eliminated jargon, and helped me amend the layout and verify content. The process used in the present study progressed from a controlled laboratory environment with specific website and GIS instructions (usability focus group) to a real world test where geographically dispersed participants received no guidance regarding how to use the site or GIS (pilot test). Extensive use of pretesting methods used in conjunction with a user centered design approach, as illustrated in this chapter, provided opportunities for participants to voice opinions about the prototype application prior to full deployment and helped create a tool appropriate for the target population. Additional research is necessary to demonstrate empirically the value of Internet GIS for disseminating water quality information regarding unregulated sources to users.

Chapter Four: Disseminating Water Quality Information Via Internet GIS

Introduction

Low level contamination of groundwater used for drinking water increases the need for users to access water quality information and visualize the chemical constituency of unregulated drinking water sources (Backer & Tosta, 2011). Previously, water quality information for unregulated drinking water sources (UDWS) has been communicated to users via flyers, brochures, television and radio advertisements, and Internet resources (A. Q. Jones et al., 2006; Kreutzwiser et al., 2011; Roche et al., 2013). Internet GIS is a promising technology for conveying water quality information to the general public since it has powerful visualization capabilities enabling users to intuitively interact with environmental data (De Freitas, King, & Cottrell, 2013; Kelly & Tuxen, 2003). However, Internet GIS applications have not been previously evaluated for their capacity to disseminate water quality information for UDWS. As a result, a need exists to evaluate the impact of GIS technology on awareness of water quality problems for unregulated sources.

As a component of this research project, I tested the hypothesis that an Internet GIS application enables users to learn about the geographic scope and severity of contaminated unregulated drinking water sources in a rural area of the United States. Specifically, I answered two research questions:

- Which features within an Internet GIS application facilitate the dissemination of groundwater quality information to users?
- To what extent does an Internet GIS application inform users about an unregulated drinking water source water quality issue?

Results indicated that a dynamic map with the ability to view attribute information about unregulated drinking water sources is a critical component of learning about contaminants. Additionally, the GIS application successfully conveyed the scope and severity groundwater contamination to a group of users who had limited prior knowledge of the visualized water quality issue. These results indicate that an Internet GIS application is one tool that successfully enables users to view and understand water quality test results for unregulated drinking water sources.

Disseminating Water Quality Information

Previous research suggests that accurate water quality information from domestic groundwater wells may influence well owner behavior (Charrois, 2010; Lucas et al., 2011; Poe et al., 1998). Though UDWS water quality information has typically been conveyed through a variety of methods (e.g., flyers, newspapers, radio and television ads, and Internet-based resources), geospatial technology and map products hold potential for increasing access to water quality information. Map products have been used in a limited number of research projects to communicate UDWS water quality information to users. One such study surveyed five chapters in the Eastern Agency on the Navajo Nation asking community members to evaluate and assess the capacity of printed maps to

communicate water quality risk for UDWS. The results of this study indicated that community members found that map products may be useful in helping people change their water habits, including deciding to obtain drinking water from less contaminated sources (deLemos et al., 2009).

However, use of printed maps may be limiting due to the lack of interactive features that are available through Internet-based GIS technology. This technology uses the distributed nature of the Internet to increase access to environmental data through use of user-friendly, interactive tools and visualizations (Jankowski, 2009). Internet GIS applications provide widespread access to scientific information about natural resources (Reed, 2008) and advance user capabilities to explore and analyze information (Khan & Adnan, 2010). Applying Internet GIS tools for UDWS water quality information dissemination addresses the knowledge gap that exists between known facts about water quality and users' awareness and comprehension of this information.

Methods

Web analytics and a survey tool were used to evaluate how members of the study population used, evaluated and understood the visualized water quality issue (described in detail in Chapter 3). Web analytics software is useful for evaluating how participants interact with the site and GIS application, and enables me to determine what GIS tools were used and at what frequency. Additionally, the survey tool was designed to assess study participants' perceptions of the GIS application, evaluate which GIS features participants found useful and determine what water quality issue study participants thought the GIS application visualized (i.e., arsenic in drinking water sources).

Web analytics.

Google Analytics (GA) is a free analytics tool hosted by Google used to monitor websites. GA has previously been used to monitor website traffic and assess visitor activity for Internet GIS applications (Werts et al., 2012). Web analytics relies on usage data to understand website and GIS application performance (Wood et al., 2003).

Previous studies have employed web analytics to evaluate technology effectiveness, education initiatives, and science communication and demonstrated that web analytics and usage data are valuable metrics for assessing website access (Veregin & Wortley, 2014). I used Google Analytics to track:

- New and returning visitors
- Traffic source (i.e., direct link to the site or from a search engine)
- Visitor geography (state level)
- Time on site
- Number of pages viewed per visit
- Time using GIS application
- Use of GIS application tools

I embedded customized JavaScript code on each website page to monitor how visitors used the site. On the GIS application page, I included JavaScript code to track Hyper Text Markup Language (HTML) event handlers for monitoring specific GIS functions such as click identification events, navigation events for resetting the map view, a spatial

analysis tool illustrating driving distance to water hauling stations and an arsenic gauge widget linked to the mouse cursor.

Survey tool.

I developed a survey for participants to complete after using the GIS application to evaluate how effectively the GIS conveyed water quality information. First, I used responses to the Likert-scaled questions to assess participant perceptions regarding the usefulness of GIS tools and functions. To accomplish this, participants responded to a series of questions (scaled from strongly disagree (1) to strongly agree (7)), evaluating the effectiveness of selected GIS features such as panning, zooming, click identification and the spatial analysis tool. These questions were modeled after similar items developed and used in other research projects (e.g., Tsou and Curran (2008); Werts et al. (2012)). Second, I asked participants to discuss the purpose of the GIS application and used thematic analysis to identify themes included in their responses.

Third, rural drinking water challenges frequently require residents to seek out alternative water sources when their primary source is contaminated. Internet GIS applications are one option for helping resource users identify nearby sources that will provide higher quality drinking water. To assess the capacity of Internet GIS for conveying this type of information I asked survey participants to interpret a figure that illustrated water hauling station locations on the NN and driving distances to reach the stations. Using a rural location on the Navajo Nation as an example, the figure illustrated driving distances to nearby water hauling stations including one within 14 miles and two additional stations within 25 miles (one way driving distance). Fourth, respondents were asked to identify map feature icons to assess their retention and comprehension of water

resource features represented on the map. I used this as a proxy for evaluating how closely a participant inspected and used the GIS. The three icons included symbols representing populated places, public water systems and water hauling stations. Lastly, I asked respondents to provide information about their experience with geospatial technology, employment type, prior knowledge of groundwater quality impairment on the Navajo Nation and comfort level with Internet-based technology. These characteristics questions were not Likert-scaled and respondents identified the answer that best described them (possible responses are illustrated in Table 4). As mentioned in Chapter 1, ENGO and IHE professionals are only one component of people who are interested in UDWS water quality. It is important to characterize the study participants to assess the generalizability of results.

The survey was administered electronically using LimeSurvey, which is an open source tool that uses a graphical user interface and enables a researcher to easily compile results (Engard, 2009). Survey design experts with the University of California-Santa Barbara Survey Center reviewed the survey for structural and linguistic issues. Also, I conducted several cognitive interviews with members of the study population to identify and reduce structural and wording problems with survey questions (Willis, 2005). Lastly, the GIS application and survey were pilot tested by 13 individuals selected from the sample population to determine if participants could access the website, use the GIS and complete the survey as intended. I analyzed all survey results and web analytics with JMP Pro 10.0.0 (2012) and employed descriptive statistics and non-parametric statistical tests to evaluate responses.

Results

I emailed the Internet GIS application link along with a letter of invitation to 99 individuals located in the western United States (Table 3). The study population included ENGO and IHE professionals in the western United States. Using the web analytics results and survey responses, I answered the two research questions. First, how did people use the Internet GIS and its tools to learn about the water quality issue? Second, to what extent does the GIS application disseminate water quality results to users?

Internet GIS use.

Google Analytics data indicated 102 site visits from 77 new visitors and 25 returning visitors during the 30-day study period (Table 3). For analysis purposes, I included only sessions that linked directly to the site and excluded four sessions that were directed to the GIS from search engines or undetermined sources. The mean session visit length was 382 seconds and ranged between zero and 2,121 seconds. When grouped by state, the longest mean session length occurred in New Mexico (698 seconds) and the shortest mean session occurred in Idaho (67 seconds). The greatest number of site visits originated from California (27 visits), New Mexico (19 visits), Oregon (14 visits) and Colorado (12 visits), which accounted for 70.6% of total visitors.

In order to understand how visitors used the GIS application, it is necessary to estimate website engagement and evaluate which GIS tools were used most and least frequently. I evaluated the number of pages viewed by visitors during their web sessions as an indication of website engagement. Analytics results indicated that visitors viewed a mean of 5.7 pages per session with a range of 1-32. I also evaluated how frequently visitors used GIS tools and functions. During an average Internet GIS session each

participant used 64 GIS functions and the total number of GIS events per visit ranged from zero to 222.

Table 3: Summary of GIS users by state including average session length.

State	\bar{X} (seconds)	Visitors (n)	Total Visitors (%)
Arizona	245.5	4	3.9
California	289.8	27	26.5
Colorado	608.8	12	11.8
Idaho	67.3	3	2.9
Montana	290.2	5	4.9
Nevada	593.5	2	2.0
New Mexico	698.0	19	18.6
Oregon	201.1	14	13.7
Utah	149.0	6	5.9
Washington	301.1	8	7.8
Wyoming	299.5	2	2.0

The GIS application was viewed by 58 unique visitors during the 30 day study period. There were four types of GIS functions available to users: a hover over tool linked to the gauge widget, map feature identification tools, a spatial analysis tool and navigation tools. Participants used the gauge widget during 54 sessions (93%), the identification tool during 37 sessions (69%), the spatial analysis tool during 28 sessions (48%) and the navigation tools during 27 sessions (47%). Overall, participants used the gauge widget 3,084 times, identified 402 map features, reset the map extent 71 times using the navigation tools and employed the spatial analysis tool 81 times (Figure 4).

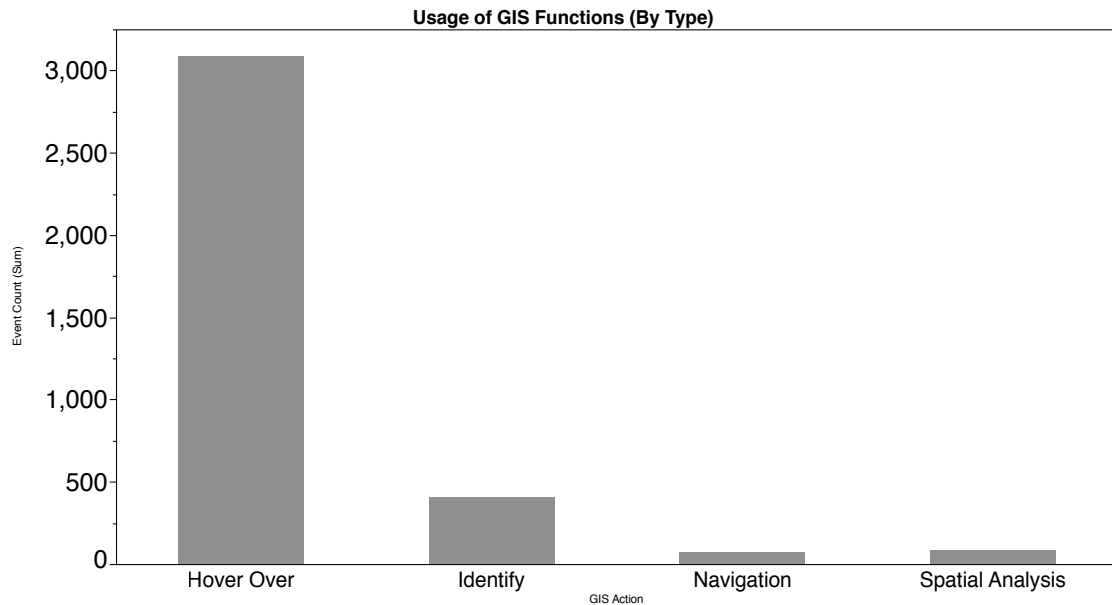


Figure 4: Summary of total GIS functions used by study participants.

Participant characteristics.

I received 38 completed surveys from 21 ENGO and 17 IHE professionals for a response rate of 67% (57 total survey responses). Four respondents started the survey yet did not complete all pages and 15 visitors opened the survey tool and did not submit any information. Since the map tool was Internet based, I sought to understand how comfortable participants felt using it via the Internet. From the survey (Table 4), 84% of participants felt “completely comfortable” with the Internet, 16% felt “somewhat comfortable” and no participants reported feeling “somewhat uncomfortable” or “completely uncomfortable” with the Internet. Survey respondents reported a range of Internet GIS experience including 58% with less than 3 years of experience (including two participants who reported no Internet GIS experience), 39% reported 3 to 10 years of

experience and 3% of respondents (1 individual) reported more than 10 years of experience with Internet GIS technology.

Table 4: Summary of study participant characteristics.

Study Participants Characteristics		Count (n)	Percentage (%)
Employment Type			
	ENGO	21	55.3
	IHE	17	44.7
Internet GIS Experience			
	< 3 years	22	57.9
	3 – 10 years	15	39.5
	> 10 years	1	2.6
Internet Comfort			
	Complete Comfortable	32	84.2
	Somewhat comfortable	6	15.8
	Somewhat uncomfortable	0	0
	Completely uncomfortable	0	0
Prior Knowledge of Water Issues in the Study Area			
	None	16	42.1
	I knew there were water quality issues, but not specifics	11	28.9
	I knew some specifics but am not an expert	9	23.7
	I consider myself a water quality expert for this area	2	5.3

Respondents also reported a range of prior knowledge regarding water resource issues in the study area including 42% with no knowledge, 29% with general knowledge about water resource challenges in the area, 24% with specific knowledge (but who do not consider themselves experts on water resources in the study area) and 5% who consider themselves experts on water quality issues in the study area. Generally, the people who responded to this survey had some experience using Internet GIS applications and little to no prior knowledge of water quality problems on the Navajo Nation (the study area).

Usefulness of Internet GIS tools and features.

The survey enabled me to assess what respondents thought about individual map features and tools. Using Likert-scaled response questions, participants reported a range of opinions regarding the effectiveness and preference for various GIS features included in the application (Table 5). Identification tools, map size and zoom functions were the most highly rated GIS tools and features. Participants strongly agreed that map panning, zooming and the identification tools were useful for evaluating the visualized water quality issue. The spatial analysis tool and lack of layer control were the lowest rated functions.

Table 5: Summary of survey responses regarding the effectiveness and usefulness of GIS map features.

Number	Question	\bar{X}^{**}	s^{**}	CI ^{**}
1	The ability to change map scale (zoom in and out) was useful	5.95	1.29	5.53-6.76
2*	I liked the ability to reposition and re-center the map	5.39	1.82	5.12-6.49
3	The legend helped me understand the map symbols	5.38	1.44	4.76-6.19
4	I wanted the ability to turn individual map layers on and off	4.32	1.86	3.15-4.85
5	The ability to click on a feature and access more information about it was useful	6.05	1.16	5.82-6.56
6	The map size was sufficiently large	5.71	1.14	5.14-6.29
7	The spatial analysis tool helped illustrate access to water hauling stations	4.50	1.91	3.83-5.59
8	I understood the terminology used in the webGIS application	5.16	1.52	4.56-5.91

*Note: This question was reversed scored originally and adjusted for this table.

** Sample mean (\bar{X}), sample standard deviation (s) and 95% confidence interval (CI) to survey questions regarding Internet GIS features. 38 survey responses.

I investigated the potential effects of non-response bias on the Likert-scaled responses since 15 respondents failed to submit any survey information. I evaluated potential non-response bias by comparing early responses with late responses (Kreutzwiser et al., 2011; Lahaut et al., 2003; Lidner, Murphy, & Briers, 2001). The survey was open for four weeks and I classified early respondents as people who responded within the first week; late respondents were individuals who completed the survey during the last week the survey was open. I identified no statistically significant difference (at an alpha level of 0.05) among late and early survey responses for any attitude questions (Table 5). These results suggest that non-response bias was limited for this study and that survey responses are representative of the broader sample population who used the GIS application and did not complete the survey.

Learning from the GIS application.

In order to assess what respondents thought the GIS application visualized, I asked people to state, in their own words, its purpose. This enabled me to assess what unregulated drinking water source challenge(s) survey respondents thought the GIS was designed to illustrate and to determine if the GIS conveyed the intended information. I used an inductive thematic analysis technique (Massey, 2011) to group responses (n=41) into themes and identified five categories including (a) contamination, (b) water source type, (c) safe drinking water access, (d) geographic extent or (e) pollution source (Table 6).

Contamination was the most commonly cited theme with 95.1% of participants indicating that the application illustrated water contamination and 80.5% of respondents specifically identified arsenic as the contaminant. For example, one respondent stated

that the application illustrated wells with arsenic contamination that “exceeded the limits set forth in the Safe Water Drinking Act.” Only one respondent addressed both the occurrence of groundwater contamination and severity of contamination in his or her response. Respondents also included information about water sources in their responses including 36.6% of respondents stating that the contaminated water sources were either unregulated, private, domestic or groundwater wells. This indicates that these participants recognized the difference between regulated and unregulated drinking water sources.

Table 6: Frequency of identified GIS themes as reported by survey respondents.

Theme	# of Statements (n)	Percentage of total responses (%)
Contamination	39	95.1
Water source type	15	36.6
Safe drinking water access	13	31.7
Geographic extent	10	24.4
Pollution type/source	6	14.6

Approximately 32% of respondents identified safe drinking water access as a GIS theme. For example, one participant wrote that the GIS application illustrated “lack of available sources of drinking water...” and another participant stated that the application illustrated “access to safe drinking water.” Eleven participants (26.9%) mentioned both safe drinking water access and water contamination in their responses. Nearly one quarter of survey respondents included information addressing the geographic scope of groundwater contamination as visualized by the Internet GIS. Only 14.6% of respondents mentioned pollution sources in their responses. Generally, answers focused

on groundwater contamination and access to safe drinking water alternatives in the study area.

I also asked participants to identify three map symbols used in the GIS application to evaluate if participants remembered the meaning of map feature icons. There were 40 responses to this question and 30% of respondents correctly identified one map feature and 70% of respondents identified three map features correctly. The participants who correctly identified only one map icon misidentified the public water system and water hauling station icons. All participants correctly identified the populated places symbol.

There were 39 individuals who interpreted the figure representing access to alternative drinking water supplies on the Navajo Nation. Of these responses, 77% (n=30) correctly interpreted the figure stating that it illustrated driving distances to water hauling stations for accessing safe drinking water instead of relying on unregulated sources. For example, one respondent stated, “The distance a resident would have to drive to obtain water from a regulated water hauling station.” The remaining responses were inaccurate interpretations of the presented figure since respondents failed to state that the figure illustrated driving distance to water hauling stations. Several participants thought the driving areas illustrated arsenic contamination levels while others were confused by the water hauling station symbol.

Discussion

GIS usage.

Internet GIS application users and survey respondents indicated that a variety of tools and functions were useful for exploring the map and learning about unregulated drinking water source contaminants. Results indicated that participants used feature

identification, panning and zooming functions to learn about UDWS arsenic contamination. The analytics information suggested that users identified map features that helped them evaluate the nature of the visualized water quality issue. For example, study participants identified more than 400 map features during GIS sessions and 60% of the identified features were unregulated drinking water sources. This suggests that accessing digital information about unregulated water well contamination helped participants evaluate the GIS purpose and understand the scope and severity of the water quality issue. Other map features such as towns, buildings and public water systems may have been less useful for evaluating the water quality problem and as a result were identified less frequently.

The survey results also suggested that participants approved of the ability to click on a map feature and view related attribute information (average rating of 6.05 out of 7). A high survey rating for the click events indicates that participants were aware of the click event tool and elected to identify features. Click events are particularly useful for conveying UDWS water quality information. The map cartography can visually convey the contamination level and the ability to access the attribute table for the map feature enables the user to view other information about the water source. For example, in this GIS application the UDWS symbol illustrated arsenic contamination as low, moderate and elevated. Information from the attribute table provided the GIS user with quantitative information indicating the measured arsenic levels (in parts per billion), the collection date and collecting agency. In the future, the displayed attribute information could be expanded to include additional contaminant information, cancer risk, suggested

frequency for water quality testing, nearby locations for water quality testing facilities or drop off locations, or other information useful to resource users.

Participants' perspectives about Internet GIS.

The exploratory nature of the Internet GIS application enabled participants to focus on geographic areas and topics of individual interest. As a result, this led to a variety of opinions regarding the application's purpose and the visualized water quality issue. When asked to articulate the purpose of the GIS application, participants identified five themes that pertained to water quality or drinking water access. Participants were able to identify a variety of aspects that inform drinking water challenges on the Navajo Nation including the widespread occurrence of arsenic in groundwater from natural sources and the prevalence of unregulated drinking water sources in rural areas. Participants stated correctly the general nature of arsenic contaminated drinking water sources in rural areas and evaluated access to safe drinking water from water hauling stations. The exploratory nature of the online map interface provided participants room to explore areas of interest, view water quality results for multiple wells simultaneously and visualize alternative water sources with safe drinking water.

The demonstrated ability of an Internet GIS application to disseminate UDWS water quality information illustrates the benefit of this technology for addressing contemporary challenges facing rural drinking water users. This type of tool enables resource users to focus on their area of interest and simultaneously view water quality information for nearby wells, which is a reported need from resource users (Flanagan et al., In Press; A. Q. Jones et al., 2006; Roche et al., 2013). Using Internet GIS applications and tools, public health officials and environmental groups can present water

quality information in a comprehensible way increasing public comprehension of water quality test results.

Previous research has not addressed the potential of Internet GIS applications for conveying water quality information to resource users. A. Q. Jones et al. (2006) and Roche et al. (2013) reported that UDWS well owners wanted to receive information via flyers or brochures mailed to their homes or newspaper and radio ads. There was a low preference for Internet resources; however, these studies did not evaluate the variety of Internet resources that may be employed to engage stakeholders. The results presented in this chapter illustrated that Internet-based geospatial technology has the capacity to convey water quality information to users who have little to no prior knowledge of the specific groundwater challenges. An Internet-based geospatial application, with powerful visualization capabilities, is one tool capable of providing water quality information to millions of Americans living in rural areas.

Conclusions

This study investigated the capacity of Internet GIS to disseminate water quality information for unregulated drinking water sources (UDWS). Previous research about UDWS quality information indicated a need to develop new tools and methods to disseminate information to resource users; however, limited research to date has investigated the role of geospatial technology for this purpose. I used an Internet GIS application designed to visualize and convey arsenic groundwater contamination of unregulated sources on the Navajo Nation to test the hypothesis that the application would convey water quality information to users. Using web analytics and a survey, I assessed what GIS tools and functions participants used to learn about the water quality

issue and evaluated how effectively the GIS conveyed information to users. I demonstrated that an Internet GIS is capable of disseminating scientific information about water quality results for unregulated sources in rural areas. Participants used the dynamic map interface to pan, zoom and access attribute information about map features. The survey results indicated that users could interpret the scope, severity and nature of groundwater contamination for unregulated sources on the Navajo Nation through using the GIS application.

The results presented in this chapter support the hypothesis that an Internet GIS application can convey water quality information about unregulated drinking water sources. Access to Internet GIS tools and applications will help the rural Americans who rely on unregulated sources understand the occurrence of drinking water contaminants. This technology provides reliable and accurate water quality information to resource users. Internet GIS applications, when appropriately designed, have the capacity to contribute to knowledge building and data access, which are critical components of raising issue awareness, affecting well owner behavior and ultimately reducing human exposure to drinking water contaminants. Additional research is necessary to better understand what, IHE and ENGO professionals think about the use of Internet GIS applications for conveying water quality information to their stakeholders. Assessment of their perspectives is critical for understanding how to employ this technology and improve dissemination of UDWS water quality information to rural, groundwater users.

Chapter Five: Perspectives Regarding Water Quality Data Access Through An Internet GIS

Introduction

Internet GIS is a useful tool for disseminating water quality information that is critical for raising issue awareness of groundwater contaminants and impacting well owners' perceptions of health risks. The research presented in this chapter was guided by one research question: Do ENGO and IHE professionals perceive an Internet GIS application to be useful for increasing issue awareness and conveying water quality information to stakeholders? The goal for this work was to identify the range of attitudes that exist among IHE and ENGO professionals regarding the benefits and challenges of using Internet GIS for disseminating water quality information. Using Q Methodology, I demonstrated that these entities value Internet GIS for its visualization and exploratory capabilities. Furthermore, the results illustrated challenges these groups face when implementing Internet GIS tools for dissemination of water quality information. The results presented in this chapter are useful for framing future discussions about when to use Internet GIS for water quality issues and for helping IHEs and ENGOs evaluate the benefits and challenges of using Internet-based geospatial technology to engage with stakeholders.

Q Methodology

I used Q Methodology (henceforth referred to as Q), to elucidate the dominant perspectives that ENGO and IHE professionals hold towards Internet GIS for disseminating water quality information to the general public. Q is a mixed method that makes use of factor analysis to identify subjective perspectives of individuals (McKeown & Thomas, 1988). This method is self-referential and uses each subject's internal frame of reference to model a perspective about a topic. The modeling is accomplished using a set of external stimuli (statements about Internet GIS and water quality in this case) that each participant rank orders in a way that is most meaningful to him or her. In Q, the participants provide meaning for the set of stimuli, not the researcher. Researchers have used Q to identify perspectives associated with a variety of environmental issues including elements of successful public participation in environmental management (Webler & Tuler, 2006; Webler, Tuler, & Krueger, 2001) and water resources challenges (Colorado Institute of Public Policy, 2006; Raadgever, Mostert, & van de Giesen, 2008; Vugteveen et al., 2010; Webler & Tuler, 2001).

Methods

A Q study consists of five stages (Watts & Stenner, 2012):

- (1) Generating a research question;
- (2) Collecting relevant statements to create the concurrence;
- (3) Narrowing the concurrence to create a set of selected statements, called the P-set;
- (4) Sorting by participants to create a unique Q-sort for each individual;
- (5) Analysis and interpretation of factors.

The context of the Q study is determined by the question the research intends to answer and a concurrence is the universe of possible statements about a subject or topic (Watts & Stenner, 2012). The concurrence for the current study is limited to statements regarding the

use of Internet GIS for providing water quality information to the general public. I assembled the concourse using a hybrid naturalistic/quasi-naturalistic approach (McKeown & Thomas, 1988). A naturalistic approach derives statements from interviews and is useful since statements mirror the language used by participants. A quasi-naturalistic approach uses information from secondary sources, such as published literature or websites. To compile the concourse of statements, I used a web-based survey, literature review and reviewed ENGO websites. My preliminary literature review suggested that data access, information availability and interactive mapping were themes for water quality information and Internet GIS.

I compiled a list of 205 potential participants including 113 ENGO researchers and advocates and 93 IHE researchers. Using a stratified random sample, I selected approximately one-quarter of the sample population ($n=56$) and generated a list of individuals to invite to participate in the first phase of this study (i.e., web survey for generating concourse statements).

Concourse generation and the P set.

Potential participants were invited (via email) to complete a four-question electronic questionnaire administered via Survey Monkey, which is an online survey software suite. The purpose of this questionnaire was to collect statements regarding access, communication capabilities and the challenges of using Internet GIS to convey water quality information to stakeholders. The questions were:

1. What do you think are the benefits of using a webGIS to communicate water quality information to stakeholders?

2. In your opinion, how does a webGIS impact access to water quality information?
3. What are the challenges associated with using a webGIS to communicate water quality information to stakeholders?
4. What potential do you see for webGIS to be used as an educational tool for water quality issues?

In addition, I identified relevant statements from academic literature published about Internet GIS.

The concourse consisted of 134 statements, which I reduced to a set of representative statements. The reduced set of statements is called a P set and is designed to capture the full range of opinions expressed in the concourse with a minimal number of statements. To aid in classification of statements, I organized the concourse statements using a 4x4 matrix (Table 7), which helped evaluate the comprehensiveness of statements selected for the P set (S. Brown, 1980). A structured P set is useful since it enables a researcher to systematically compile a set of representative statements and to include theoretically valuable statements (Dryzek & Berjikian, 1993; Watts & Stenner, 2005, 2012; Woolley & McGinnis, 2000). Statements were classified into four categories: access, equity, data and technology.

Once statements were classified, I applied Toulmin's heuristic for additional classification (Dryzek & Berjikian, 1993). There are four types of claims that comprise a P set (Woolley & McGinnis, 2000) including (a) definitive statements, concerning meaning of a term; (b) designative statements, regarding questions of fact; (c) evaluative

statements, assessing the value of something; and (d) advocative statements, making recommendations about the use of the object of interest. A typical P set includes 40-60 statements; although, previous studies have used as few as 20 statements (S. Brown, 1980; Robbins, 2006). Using Toulmin's heuristic, I selected 34 statements that represented a range of opinions while maintaining an overall low number of statements to maximize study participation (Appendix C.).

Table 7: Classification of P set statements.

Type of Claim	Statement Type*			
	Access	Equity	Data	Technology
Definitive	0	0	1	1
Designative	1	1	4	8
Evaluative	3	2	3	2
Advocative	2	4	1	1

*Note: Cell values indicate the number of statements selected per category

Q sort: Participant sorting of statements.

Following selection of the P set statements, I arranged for participants to sort the statements and model their perspectives about Internet GIS and water quality. The sorting procedure was facilitated by FlashQ (Hackert & Braehler, 2007). FlashQ is an online software that is accessible through an Internet browser, has a high degree of customization and software support, and hosting through Qsortonline.com. I used an Internet-based sorting program since participants were expected to have Internet access and a high level of comfort with Internet applications. Additionally, I invited participants from a wide geographic area (the western United States) making in-person Q sorts logistically challenging. Previous research has demonstrated the validity of online Q studies (Reber, Kaufman, & Cropp, 2000; Van Tubergen & Olins, 1979).

Each participant rank ordered the P set statements from most disagree to most agree using a sorting range from -4 to +4 with a kurtosis similar to a normal distribution (S. Brown, 1980). This response grid shape encourages participants to prioritize statements (Webler, Danielson, & Tuler, 2009). Once each participant completed the Q sort he/she was prompted to explain the rationale for placing statements in the most agree or most disagree categories.

After data collection, I used factor analysis to identify common rank ordering patterns (Robbins, 2006; Webler, Danielson, & Tuler, 2007). A factor represents an operational definition of an attitude based on human behavior, rather than an ad hoc or arbitrary classification (S. Brown, 1980). Using PQMethod, a statistical software package designed specifically for Q analysis, I extracted six factors (using centroid method) and then aligned the factors using varimax rotation (Watts & Stenner, 2012). Of the six extracted factors, I retained a factor if: (a) it had an Eigen value greater than one, (b) two or more Q sorts loaded significantly, and (c) the factor had theoretical significance (Watts & Stenner, 2005; Webler et al., 2001). Factor loading was evaluated at an alpha level of 0.01, which is commonly used for Q studies (S. Brown, 1980).

Participants also reported their experiences with water resources, geospatial technology, employment type and where they live (state level) to understand some of the characteristics of the respondents. I invited 62 IHE and ENGO professionals to complete Q sorts. My sampling approach was non-random and decidedly purposeful since Q works best when participants have well developed opinions about the issue under investigation (S. Brown, 1980; Watts & Stenner, 2012).

Results

Nineteen participants completed Q sorts including eight ENGO and 11 IHE professionals for a participation rate of 31%. The study participants reported a range of water resources and GIS experience (Table 8). As shown, overall, participants were experienced in GIS and water resources with few individuals having minimal experience in either area. Study participants were recruited from California (n=8), Arizona (n=4), Colorado (n=2), Oregon (n=2) and one participant each from Montana, Nevada and Utah.

Table 8: Characteristics of Q study participants.

Study Participant Characteristics		Count (n)	Percentage (%)
Employment type	ENGO	8	42
	IHE	11	58
Water resources experience	< 3 years	2	11
	3-5 years	2	11
	> 5 years	15	78
GIS experience	< 3 years	6	32
	3-5 years	2	11
	> 5 years	11	57
Internet GIS experience	< 3 years	9	48
	3-5 years	5	26
	> 5 years	5	26

The factor analysis results indicated four factors of statistical and theoretical significance. The factors represented 43% of observed variance and addressed issues of access, education and technology. Of the 19 sorts completed by participants, 16 loaded significantly on a factor and three sorts did not load significantly on any factor. No sorts loaded significantly on multiple factors. The four identified factors represent distinct

opinions regarding the use of Internet GIS for disseminating water quality information to the general public.

Factor A: Citizen education.

Respondents who identified most strongly with this perspective agreed that an Internet GIS application increases access to water quality information in a user-friendly manner. Furthermore, these types of applications support citizen education and information communication as illustrated by the statements in Table 9.

Table 9: Distinguishing statements for Factor A: Citizen Education.

Z - Score	Statement
1.68	I think webGIS increases access to water quality information and presents the information in a user-friendly way that is easier to understand than raw data.
1.49	I believe these programs are the future for communicating accurate science in a way that general public can understand. It is spatially relevant, and the associated reports and data increase their ability to understand and interpret water quality data.
1.28	webGIS could support education of citizens, students and policy makers on water quality issues.
1.25	Despite the challenges, I think webGIS is still a very useful educational tool for water quality issues and can reach a younger audience who are more web-savvy.
-1.25	Users can use various plots of water quality and can generate testable hypotheses.
-1.25	Although webGIS is great for display it still lacks the ability to perform complex analyses.
-1.31	Depending on data securities, individuals can access available data and explore data sets on their own.
-1.43	I think that a webGIS program is an egalitarian way for all people to access data.

For this factor, the educational value of an Internet GIS is associated with its visualization capacity and the illustration of where water quality is monitored.

Participants who identified most strongly with Factor A did not think that water quality

data or databases presented a challenge to using Internet GIS. Statements regarding data availability and water quality database challenges loaded strongly negative for this factor, which suggests that participants associated with this factor do not view data or data access as significant limitations for Internet GIS. This factor illustrates that IHE and ENGO professionals support using Internet GIS applications for disseminating water quality information and educating the general public about contaminant issues. This supports the use of Internet-geospatial technology for resolving the education and environmental data access challenges that exist for unregulated drinking water sources.

Factor B: Access optimists.

This factor represents individuals who think Internet GIS increases access to environmental data; though, this technology has limited education value due to differential Internet access, speed and reliability among the general public (see Table 10). Participants who loaded onto this factor think that Internet GIS is a valuable tool for viewing environmental data and raising issue awareness among the general public. For this factor, improved access to water quality information was related to the ability to see the information in a spatially explicit setting. One participant stated that GIS applications are easier to understand than alternative forms of presenting water quality information, such as tables. The use of open source or license free software also provides an increased capability for IHEs and ENGOs to use GIS technology since it reduces some of the financial costs associated with acquiring the technology.

Table 10: Distinguishing statements for Factor B: Access Optimists.

Z - Score	Statement
1.84	It greatly improves access because you don't need to use licensed and/or complicated software to view and use the data.
1.82	Benefits of webGIS include being able to portray the location of data and its attribution.
1.47	We benefit from being able to link our constituents graphically to their watershed as well as to be able to allow place this information on our website and make it interactive.
-0.88	Some people are not comfortable with the technology and need basic training if they are going to use it themselves.
-0.91	Slow internet connections could be a problem.
-1.27	I think one challenge with any GIS system is that too much data can overwhelm people who are not data scientists.
-1.98	We also have partners that do not have reliable internet connection, so that can make things challenging as well.

By using an Internet GIS, citizens may explore water quality data and not be overwhelmed by unstructured, raw environmental information. Participants who loaded highly onto this factor did not view accessing the Internet or digital environmental data through an Internet application to be a challenge for the general public; slow and unreliable Internet connections, and the need for Internet training were not considered significant issues. Concerns regarding Internet access and environmental education are noticeably unimportant for this factor. Study participants thought that few people are uncomfortable using the Internet; although, they did state that Internet technology has greater appeal for younger people. This perspective primarily emphasizes the use of Internet applications to provide access to information and does not include concerns regarding reliability, environmental education or computer access. Factor B illustrates a subset IHE and ENGO professionals who think that Internet GIS technology has the capacity to increase access to water quality information in rural areas since Internet

access is not considered an impediment. This factor is similar to Factor A (Citizen education) though it emphasizes the capacity of the tool for increasing information access and not its education value.

Factor C: Digital divide.

Participants who loaded highly on this factor view Internet GIS as a tool that can increase public access to water quality data; however, access barriers due to socioeconomic conditions limit the impact of this technology on environmental education among the general public (Table 11). Participants agreed that Internet GIS could present water quality information in a user-friendly manner and increase citizen access to environmental information. However, for this factor, participants thought that the technical challenges of creating an appropriate spatio-temporal database remain difficult to address. Use of a relational database instead of a flat file, for example, provides greater flexibility in exploring and analyzing water resources data; however, expertise is necessary to create and population the database (Horsburgh et al., 2008). Furthermore, people aligned with this factor think that Internet GIS applications generally lack the complex spatial analysis capabilities useful for conveying water quality information and hypothesis testing.

This factor differs from Factor B due to concerns regarding the ability of citizens to access the Internet. Statements about the Internet providing easy access due to widespread and reliable information technology services loaded strongly negative. This represents a perspective that values the visualization capabilities of Internet GIS technology, but views the ability of citizens to access information through an online tool to be limited due to Internet access disparities. As a result of these challenges, people

who align with this factor think that Internet GIS has limited education capability for people without Internet access or who have a slow and unreliable Internet connection.

Table 11: Distinguishing statements for Factor C: Digital Divide.

Z - Score	Statement
1.72	I think webGIS increases access to water quality information and presents the information in a user-friendly way that is easier to understand than raw data.
1.41	The potential might be limited by the stakeholder's willingness to actively pursue water quality information that is collected scientifically.
-1.11	We also have partners that do not have reliable internet connection, so that can make things challenging as well.
-1.24	I think that a WebGIS program is an egalitarian way for all people to access data.
-1.47	Access to the information in this form will greatly improve public education.
-1.62	Easy access - most folks use the web these days.

Factor D: Technical skeptics.

This factor diverges from the three previous factors, which supported the use of Internet GIS for disseminating water quality information. Factor D represents people who think that Internet GIS does not increase access to water quality information and has minimal education value for water quality issues due to lack of training, skills and technology access among the general public (see Table 12). People who align with this perspective think there exist important limitations for using an Internet GIS application to represent the management complexities of water quality issues. Furthermore, people aligned with this factor think that water quality regulations are complex and inclusion of these complexities in an Internet GIS environment is difficult to achieve.

Factor D represents the attitude that it is challenging to create a fully functioning database that includes both spatial and temporal information for continuous water quality monitoring. This factor also includes the opinions that the representation and visualization of large amounts of environmental data is challenging for non-scientists to understand and may overwhelm individuals from the general public. People who identified with this factor think that GIS visualization of information has limited impact on individual understanding of water quality issues due to challenges understanding large amounts of environmental data.

Table 12: Distinguishing statements for Factor D: Technical Skeptics.

Z - Score	Statement
1.62	Water quality changes over space and time, so creating a fully functioning spatiotemporal database with continuous monitoring data might be a challenge.
1.47	I think one challenge with any GIS system is that too much data can overwhelm people who are not data scientists.
1.34	Water quality regulations are very complex, so a map-oriented portrayal of data can be interpreted in many ways.
1.00	Making sure that those who want the info have the necessary hardware, web access, and skills to use the web GIS.
-1.01	Access to the information in this form will greatly improve public education.
-1.14	I think webGIS increases access to water quality information and presents the information in a user-friendly way that is easier to understand than raw data.
-2.28	Easy access - most folks use the web these days.
-2.28	I think that a WebGIS program is an egalitarian way for all people to access data.

This factor includes strong negative loading from statements associated with equal and universal access to citizens and interested participants. For people who identify with this attitude, the benefits of using an Internet GIS for water quality

education and public engagement are limited by design challenges, complex water quality regulations and unequal access to Internet applications among the general public. People who align with this factor think that an Internet GIS is unsuitable for engaging with stakeholders. The occurrence of this perspective indicates that not all IHE and ENGO professionals support the use of Internet GIS technology for conveying water quality information to the general public.

Discussion

Using Q Methodology, I identified four attitudes associated with Internet GIS and water quality data among the study population and illustrated the fundamental differences that exist among the perspectives. Three of the four attitudes aligned with using Internet GIS to disseminate water quality information and contribute to environmental education; however, only one of these perspectives unequivocally advocated for using Internet GIS technology for this purpose. Factor A illustrated the view that Internet GIS is an underutilized tool that has value for engaging stakeholders and presenting water quality information in a spatial context. Participants who identified with this factor demonstrated a preference for using Internet GIS as an education and visualization tool that will enable users to view water quality information for multiple sources in an area. This factor supports observations made by G. Brown (2012), that Internet GIS can be used successfully to raise issues awareness. It also aligns with the conclusions made by Haklay (2003), Kelly and Tuxen (2003) and De Freitas et al. (2013) that geospatial technology is valuable for enabling greater access to environmental information.

Linking this perspective to stated research needs for UDWS, some ENGO and IHE professionals think there exists an opportunity to develop and use these types of

tools to address issue awareness, impact water quality testing behavior and increase access to water quality information. For example, the map interface employed with an Internet GIS enables users to view water quality results for multiple water sources simultaneously. This is particularly useful since several studies reported that UDWS resource users reported a need to view the water quality information for wells in addition to their own (Flanagan et al., In Press; A. Q. Jones et al., 2006; Roche et al., 2013).

Factors B and C represent attitudes that view the education and dissemination capabilities of Internet GIS to be tempered by technology and accessibility challenges. These perspectives align much more with previously reported results regarding tools useful for conveying water quality information. Factor B, for example, includes the attitude that Internet GIS has great potential for disseminating water quality information since a map interface enables users to view information in a spatial context. However, accessing this information is potentially challenging due to slow Internet speeds and limited connection reliability in rural areas. In the United States between 67 and 95% of rural households have broadband Internet access (National Broadband Map, 2014; USDA, 2013); although, Internet speeds are generally lower in rural areas compared to urban locations (National Broadband Map, 2014). Despite concerns regarding Internet access there remains great potential and opportunity for using this technology in rural areas.

Factor C raises similar concerns regarding Internet GIS and access, yet is much more aligned with issues associated with the digital divide. The digital divide is a concept that addresses disparities in access to and use of information technologies, such as the Internet (Chakraborty & Bosman, 2004). As noted however, as much as 95% of

rural households in the United States have Internet access so concerns regarding Internet access needs to be addressed at a local scale where deviations from the national average are greater (National Broadband Map, 2014). Individuals aligned with this factor also agreed that the ability of an Internet GIS application to convey water quality information depends on citizen interest in using online tools. Using the Internet to acquire information is not a universal interest among the general public and other tools may be more effective for disseminating water quality information. For example, Pocewicz et al. (2012) observed that Internet GIS applications for public participation in environmental management have lower participation rates when compared to paper participatory approaches. For people who align with this perspective, it is critical to evaluate Internet access and speed as well as gauge public interest in using online tools to dissemination information among the general public.

People aligned with Factor D do not support the use of Internet GIS as a tool for engaging with the general public regarding water quality issues. For this factor it is important to ensure that interested people have the skills to use, understand and create testable hypotheses regarding the presented water quality information. This represents the viewpoint that members of the general public have limited interest in using online resources to understand water quality issues. Concerns regarding the education and skills necessary to use and interpret the GIS application aligns with concerns expressed by Merrick (2003) who stated that GIS applications designed for public use suffer from limited cognitive access due to education and technical barriers of the general public. Additionally, there remain 5-37% of rural US households that lack broadband Internet access. Therefore, for rural areas, using the Internet as a means to disseminate

information presents a set of challenges that cannot be addressed directly by education and outreach organizations. The basic infrastructure required to support Internet access is commonly absent or underdeveloped in these areas; including the same rural areas where residents rely heavily on unregulated groundwater resources for drinking water.

Among researchers, educators and that work directly with stakeholders, several perspectives exist that perceive Internet GIS to be a tool that will raise issue awareness about water quality issues, despite previous study's results suggesting a low interest among resource users for using Internet resources to access water quality information. Compared to previous UDWS research, Q Methodology better informs researchers about the challenges and limitations associated with using Internet-based geospatial technology for the dissemination of water quality information. Results from this study contradict previous research regarding tools for disseminating water quality information (A. Q. Jones et al., 2006; Kreutzwiser et al., 2011; Roche et al., 2013). The results presented in this chapter illustrate that IHE and ENGO professionals think that Internet GIS technology is a useful tool for conveying water quality information to the general public.

However, there exists no agreement on the value of Internet GIS among the study population with another subset of the study population believing that the technology is unsuitable for conveying water quality information to the general public. Illustration of these incongruent perspectives highlights the need to address issues of access, education and interface design when considering using an Internet GIS application. These attitudes also illustrate fundamental differences regarding the value of geospatial technology for engaging with the general public. In particular, there were important differences among study participants regarding the accessibility and user-friendly nature of Internet

applications; although, the prevalence of these perspectives is unknown. Q method is limited to identifying the existence of these perspectives and is not suited to assessing the prevalence of these attitudes among the study population. Rather, Q is a starting point for future research seeking to resolve these challenges and identify practices for best applying geospatial technology for unregulated drinking water source issues.

Conclusions

Identification of these four factors suggests that Internet GIS is one tool that is capable of disseminating water quality to the general public; however, there remain concerns about the benefits of this technology for rural areas stemming from Internet access and reliability challenges. One subset of the study population supports using Internet GIS as an educational tool that increases access to water quality information; another subset of the study population does not support the use of Internet GIS due to concerns regarding Internet access, general environmental education of the general public, and challenges designing and maintaining Internet-based geospatial technology. Additional research is necessary to better understand how to resolve these conflicts notions regarding the value of Internet GIS for water quality information dissemination.

Compared to previous research, the results I presented in this chapter more rigorously examined the potential benefits and limits of Internet GIS for conveying unregulated drinking water source information to the general public. For ENGO and IHE professionals that engage in public education regarding water quality issues, these results indicate that there is value in using geospatial technology to teach people about their drinking water supplies. This research lays the foundation for additional research investigating how common these four perspectives are among IHE and ENGO

professionals and for a case study evaluation of best practices for implementing Internet GIS technology to address rural drinking water contamination.

Chapter Six: Conclusions And Recommendations

Chapter 6 summarizes the main study components including the problem statement, participants, research questions, methods, results, and study limitations. Chapter 6 also provides conclusions based on results leading to recommendations for further study.

Problem Statement

A gap continues to exist between that which is known about drinking water quality and the public's awareness and understanding of these known issues. Access to safe and reliable drinking water is critical for maintaining human health, especially for people whose drinking water sources are unregulated. In the United States, approximately 43 million Americans acquire drinking water from private, domestic sources, which unlike public sources, are not regulated by the Safe Drinking Water Act of 1974. Water quality from these unregulated sources is generally unknown and, in cases where water quality has been evaluated, the general public often experiences difficulty acquiring and understanding the results. The quality of water from unregulated sources is of particular concern within rural areas of the United States since contaminants, such as arsenic, commonly occur and may cause deleterious human health problems. The lack of resource user knowledge and awareness about water quality is of particular concern to public health and environmental organizations since people may unknowingly consume contaminated drinking water.

Therefore, providing stakeholders with knowledge about water quality issues that is easily accessible and understandable represents a recurring challenge in today's society. In particular, elevated arsenic levels in unregulated drinking water sources significantly impacts users located in many rural areas in the United States. Further study is required to identify the most relevant dissemination strategies to inform rural residents about unregulated drinking water quality. To investigate strategies for helping the general population become more informed of rural water quality issues, I researched the potential effects of Internet GIS technology, since it conveys environmental information to users in a clear and effective manner.

Study Participants

The study population included water resources research and advocate professionals employed at environmental nongovernmental organizations (ENGOS) and institutions of higher education (IHEs) in the western United States. Individuals from these entities were selected due to their critical roles in (a) employing GIS technology and geospatial data in environmental decision-making processes; and, (b) disseminating current information about drinking water quality issues to users in rural communities. Input from professionals in these two educational entities informs researchers of the value and possibilities in using Internet GIS as one tool to disseminate water quality information to rural residents.

Research Questions

Three research questions guided the development and implementation of this study:

1. Which features within an Internet GIS application facilitate the dissemination of groundwater quality information to users?
2. To what extent does an Internet GIS application inform users about an unregulated drinking water source water quality issue?
3. Do ENGO and IHE professionals perceive an Internet GIS application to be useful for increasing issue awareness and conveying water quality information to stakeholders?

Responses to these research questions provide necessary information to assist in addressing the existing gap between what is known about the quality of unregulated drinking water sources (UDWS) and what rural resource users know about their drinking water. The research questions and associated results are applicable to private groundwater wells in rural areas of developed countries, having implications for use of geospatial technology to convey water quality information to resource users.

Methods

Study methods included (a) User Centered Design framework to design and deploy an Internet GIS application, (b) web analytics and survey to collect information regarding GIS usage and user opinions about GIS features, and (c) Q Methodology to evaluate perspectives held by ENGO and IHE professionals toward using Internet GIS for disseminating water quality information. I designed and deployed an Internet GIS application to visualize arsenic groundwater contamination of unregulated drinking water sources on the Navajo Nation, in the southwest United States. I employed a User Centered Design framework to create a GIS application interface appropriate for use by

the target population. This multistep design process included a usability focus group, expert review of content and a pilot test to critically assess the design and suitability of the GIS application.

Once developed, ENGO and IHE professionals used the GIS application and completed a follow-up survey. Applying Google Analytics, I evaluated the GIS tools and functions most and least employed by users. The survey collected four types of information about the users and GIS application. First, the survey included questions to assess user impressions of the visualized water quality issue (i.e., arsenic contamination of unregulated drinking water sources). Second, survey respondents evaluated output of a spatial analysis tool illustrating access to safe drinking water supply locations on the Navajo Nation. Third, responding to a series of questions using a seven-point Likert scale ranging from strongly disagree (1) to strongly agree (7), participants reported on the usefulness of various GIS tools and features. Lastly, demographic information was collected about study participants' experiences with GIS technology, the Internet and other characteristics useful for generalizing the study findings.

I also determined the perceptions of ENGO and IHE professionals regarding the capacity of Internet GIS for conveying water quality information to stakeholders and raising awareness of water quality issues. Q Methodology, which is a mixed methods approach that relies on factor analysis to model participants' opinions, was employed to identify the dominant perspectives that exist among ENGO and IHE participants. For a Q study, the researcher selects a set of statements that participants use to model their opinions. Each participant, in turn, rank orders the statements from most disagree to most agree creating an output known as a Q sort. The researcher compiles Q sorts from

all participants and uses factor analysis to identify common patterns among the arrangement of the statements. Factors are identified patterns that present an operational definition of a perspective held by study participants. The Q approach is useful for evaluating the underlying factors influencing opinions about a topic to systematically study human subjectivity.

Summary Of Results

GIS users employed the panning, zooming and click identification tools to assess and understand the visualized groundwater quality problem. Participants strongly approved of the navigation, identification and dynamic map legend features of the application. More than 400 map features, 60% of which were unregulated drinking water sources, were identified. Furthermore, the GIS application successfully visualized contamination of drinking water sources on the Navajo Nation, with over 80% of users accurately identifying arsenic as the specific contaminant. The Internet GIS spatial analysis tool also informed users of access to safe drinking water at water hauling stations in the study area.

ENGO and IHE professionals held four perspectives toward using Internet GIS to convey water quality information to stakeholders. Three perspectives were supportive of using Internet GIS to communicate water quality information, with the caveat that Internet access and stakeholder interest in using Internet-based tools may be limiting factors. The fourth perspective did not support using Internet GIS to educate stakeholders about water quality issues, within certain parameters. Users did not support the use of Internet GIS as a tool for disseminating water quality information when disparate Internet access and socioeconomic conditions preclude universal access to

information technology and services. Instead, they preferred to rely on more traditional, less technological methods (e.g., flyers, brochures, advertisements) since they found these tools more user-friendly and easier to access. These results indicate multiple perspectives among the study population regarding the benefits and potential for using Internet GIS to convey water quality information to stakeholders. Therefore, additional research should be undertaken to further clarify and resolve potentially conflicting perspectives. However, it should be noted that three of the four identified perspectives supported the use of Internet GIS as a tool to inform stakeholders about water quality issues from rural unregulated sources.

Study Limitations

The study has limitations providing boundaries for generalization of findings. First, this study is limited to ENGO and IHE professionals, representing one segment of the general public. Overall, though not universal, the study participants were experienced with geospatial technology. Additionally, users had reliable access to broadband Internet and were comfortable using Internet technology. Interpretation of findings must consider these factors, since they may not be representative of all potential Internet GIS users in the general public. Second, the visualized rural groundwater quality issue was limited to arsenic, which is one of several contaminants known to occur regularly in groundwater wells. The visualization and accessibility of water quality information for arsenic contaminated wells is likely similar to the information challenges for other groundwater contaminants, though this study did not address this issue with other contaminants.

Third, the study area was limited to the Navajo Nation, which is a rural area in the southwestern United States. While this area experiences many of the same drinking

water challenges as other rural areas of the US, unique aspects to the study area exist, such as the high prevalence of residents needing to haul drinking water from unregulated groundwater wells. Lastly, Q Methodology is a highly valuable and relevant method that helps researchers identify dominant opinions that exist among the study population regarding Internet GIS and water quality. Q enables researchers to identify and assess fundamental differences among perspectives that are key to resolving potential conflicts. This method, however, does not enable one to assess the extent to which any single opinion is represented among respondents. Therefore, Q results are limited to only identification for the purpose of systematically studying subjectivity and identifying key areas of agreement or conflict among perspectives. Additional forms of analyses are necessary to expand upon the Q results of this study and to determine how common the identified perspectives are among the study population.

Conclusions

Within the study parameters discussed above, several conclusions are drawn supporting the generalization of project findings. Overall, based on the perspectives of the participating water resources professionals, results obtained from this study support the hypothesis that an Internet GIS has the capability to provide users of unregulated drinking water sources with increased access to water quality information. Specifics reflecting this overall research conclusion include:

1. GIS technology successfully illustrates the contamination of unregulated drinking water sources in a rural area of the United States, supporting previous research suggesting the value of interactive GIS to visualize environmental issues;

2. ENGO and IHE professionals report that Internet GIS technology is a valuable tool for engaging with the general public, which is a finding that conflicts with select previous research;
3. Dynamic map features are effective in demonstrating the scope and severity of arsenic contaminated groundwater, supporting previous research suggesting the value of maps to convey information about environmental issues to the general public;
4. Internet-based geospatial technology provides access to environmental information, presenting material in a manner that is comprehensible to the general public;
5. A user-friendly interface design, achieved through a User Centered Design framework, increases access to environmental information enabling users to view water quality results simultaneously for multiple well locations;
6. User ability to understand the visualized groundwater contamination issue does not appear to be dependent on specific levels of previous GIS experience or prior knowledge of water quality issues; and,
7. Though a valuable tool for engaging the general public, divergent views exist regarding the value of Internet-based geospatial technology for displaying water quality issues, due primarily to concerns regarding access and connectivity in rural areas.

In summary, Internet GIS technology is one tool capable of reducing the existing gap between that which is known about drinking water contaminants in rural unregulated

groundwater sources and the public's awareness and understanding of those known issues. A user-friendly interface enables GIS users to access and interpret water quality results. Overall, Internet GIS is a tool that ENGO and IHE professionals, as well as other water resource advocates, should consider using with stakeholders to (a) increase access to water quality information, (b) raise issue awareness about groundwater contaminants, and (c) inform them of the chemical composition of their drinking water. Ultimately, this may lead to a decrease in contaminant exposure resulting from changes in well owner behavior in rural geographic areas of the United States.

Recommendations for Further Study

This study investigated the value of using Internet GIS to inform rural water users of quality issues associated with unregulated water sources from the perspectives of ENGO and IHE research and advocate professionals in the western United States. Based on project conclusions, several research recommendations are made to further advance the study of water quality at the intersection of rural geographies and unregulated drinking water sources. Three specific recommendations are suggested:

- Research is needed to further clarify best practices that ENGO and IHE professionals may use to engage rural stakeholders in the use of an easily accessible Internet GIS for understanding quality issues with unregulated drinking water sources.
- Perceptions of stakeholders served by ENGO and IHE research and advocate professionals should be solicited to clarify the extent to which they value the use of Internet GIS as a tool for conveying information

about drinking water quality issues. Specifically, research is needed to determine if and under what conditions rural stakeholders value Internet GIS technology for accessing water quality information. Stakeholder perspectives should, in turn, be considered relative to those of ENGO and IHE professionals to best inform dissemination practices about rural water quality issues.

- The present study emphasized only arsenic groundwater contamination, which is one of several contaminants commonly found in rural, unregulated water wells. Therefore, additional research is needed to address the capacity of geospatial technology for conveying information regarding other water contaminants (i.e., radionuclides, nitrate and microorganisms), to determine if results are similar to those found for arsenic.

Results from these recommended study topics will add to the findings of this research by further evaluating the impact that Internet GIS has on rural stakeholder perceptions of drinking water contamination, human health risk, and well owner behavior. Ultimately, the above research recommendations also support evaluating and comparing the effectiveness of different dissemination tools (e.g., Internet GIS, flyers, brochures, advertisements), thereby informing water resource professionals of best practices for conveying water quality information to rural unregulated groundwater users.

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Appendices




Appendix A: Definition of Terms

- Arsenic: Element 33 in the periodic table; a semi-metallic element that is tasteless, odorless and is commonly found in either the +3 or +5 oxidation state. Reported concentrations refer to dissolved arsenic in water in micrograms (µg) per liter.
- Environmental Nongovernmental Organization (ENGO): A tax exempt organization that operates at the local or regional scale, has a mission statement that includes advocacy, development, education and research and is oriented towards water resources or water quality issues.
- Internet Geographic Information Systems: “A network based geographic information service that utilizes both wired and wireless Internet to access geographic information, spatial analysis tools and GIS web services” (Peng & Tsou, 2003).
- Maximum contaminant level (MCL): The greatest allowable level of a contaminant in drinking water, as defined by the Safe Drinking Water Act. The current arsenic MCL is 10 micrograms per liter (10 µg per liter).
- Regulated water source: A public water system that meets the requirements for regulation by the Safe Drinking Water Act: A system that provides water for human consumption that has 15 or more connections or serves more than 25 people per year. This includes community water systems, non-transient non-community water systems and transient non-community water systems.
- Unregulated drinking water source (UDWS): A water system or source that is not regulated by the Safe Drinking Water Act including private, domestic water wells.
- Water hauling station: Water hauling locations where individuals can access drinking water that is regularly tested for microbial and chemical contaminants.
- Western United States: States including Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming.

Appendix B: Survey Tool

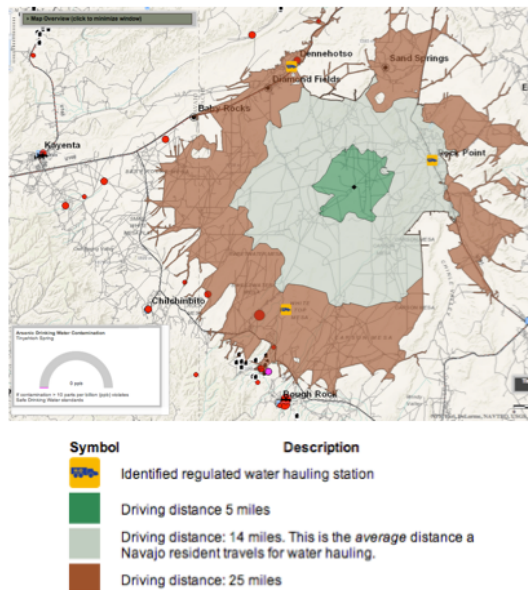
Section I – GIS Purpose

1. How much time did you spend using the webGIS applications (from a timer on the webGIS page):
_____ Minutes _____ Seconds
2. In two or three sentences, what environmental problem do you think the webGIS application illustrated?
3. Based on your use of the webGIS application, please match each symbol with the appropriate description:

Description			
Town	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Public Water System	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Regulated Water Hauling Location	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Using the figure please answer questions 4 and 5:

4. What is the meaning associated with each colored polygon?
5. What does the figure illustrate about water hauling driving distances?



Section II - Please rate each item below in how it helped you understand the visualized groundwater quality issue

Likert-scaled responses, 1-7. 1= Strongly disagree and 7 =Strongly agree.

6. The ability to change map scale (zoom in and out) was useful
7. I disliked the ability to reposition and re-center the map
8. The legend helped me understand the map symbols
9. I wanted the ability to turn individual map layers on and off
10. The ability to click on a feature and access more information about it was useful
11. The map size was sufficiently large
12. The “Water Hauling Station Locator” tool helped illustrate access to water hauling stations
13. I understood the terminology used in the webGIS application

Section III - Respondent Information

14. With what type of organization are you primarily affiliated?
 - Environmental nongovernmental organization (ENGO)
 - Institution of Higher Education (IHE)
15. (If ENGO): At what level does your organization primarily operate? Please check all that apply.
 - Community
 - Regional

- National
- International

16. (If ENGO): Does your organization's mission include any of the following?
Please check all that apply:

- Education
- Research
- Advocacy
- None of the above

17. (If IHE): What is your primary area of research? Please check all that apply.

- Physical science
- Social science
- Health science
- Other _____

18. How much experience do you have using geographic information systems (GIS)?

- No experience
- Less than 1 year
- 1-3 years
- 3-5 years
- 5-10 years
- More than 10 years

19. How much experience do you have using web-based GIS applications?

- None
- Less than 1 year
- 1-3 years
- 3-5 years
- 5-10 years
- More than 10 years

20. How comfortable are you using the Internet?

- Completely uncomfortable
- Somewhat uncomfortable
- Somewhat comfortable
- Completely comfortable

21. Do you have prior knowledge of water quality issues in the Four Corners area?

- None
- I knew there were water quality issues, but not the specifics
- I knew some specifics but do not consider myself an expert
- I consider myself a water quality expert for this area

Appendix C: P Set Statements

1. The potential might be limited by the stakeholder's willingness to actively pursue water quality information that is collected scientifically
2. I think webGIS increases access to water quality information and presents the information in a user-friendly way that is easier to understand than raw data.
3. It greatly improves access because you don't need to use licensed and/or complicated software to view and use the data.
4. We have partners that do not have reliable internet connection, so that can make things challenging as well.
5. I see how it could be great for sharing data sets for students to use and then updating as needed.
6. Access to the information in this form will greatly improve public education.
7. Easy access - most folks use the web these days.
8. My experience is that all GIS and non-GIS databases for water quality information are difficult to use, at least to some degree.
9. I think that a WebGIS program is an egalitarian way for all people to access data.
10. Could be useful in an instructional setting.
11. I think the challenges associated with using a webGIS to communicate water quality information are not with the webGIS itself but with the act of effective communication.
12. webGIS could support education of citizens, students and policy makers on water quality issues.
13. I believe these programs are the future for communicating accurate science in a way that general public can understand. It is spatially relevant, and the associated reports and data increase their ability to understand and interpret water quality data.
14. WebGIS is an Internet based technology that enables users to browse, query, and display spatial data using a standard web browser.
15. Users can use various plots of water quality and can generate testable hypotheses.

16. Water quality regulations are very complex, so a map-oriented portrayal of data can be interpreted in many ways.
17. Benefits of webGIS include being able to portray the location of data and its attribution.
18. Depending on data securities, individuals can access available data and explore data sets on their own.
19. Seeing where water quality measurements help people see where they live and recreate in relation to the water quality problem and nonproblem areas.
20. I've had difficulty identifying the data that I need for specific questions I'm trying to answer.
21. You would have to make sure you have the right data and that it is "cleaned up" enough for use.
22. I think it can be effective so long as the students have a firm basis in the methods of data collection and scientific analysis before undertaking an effort to understand the GIS backend products.
23. A web-based Geographical Information System (GIS) is an online tool to represent spatial information over the internet.
24. Stakeholders do not understand uncertainties created using various interpolation techniques and they will not take time to understand data tools.
25. Folks think the webGIS graphic is the result and don't understand that it is just a convenient tool to look at the real product, which is the data and the analysis of that data.
26. Some people are not comfortable with the technology and need basic training if they are going to use it themselves.
27. Although webGIS is great for display it still lacks the ability to perform complex analyses.
28. Water quality changes over space and time, so creating a fully functioning spatiotemporal database with continuous monitoring data might be a challenge.
29. I think one challenge with any GIS system is that too much data can overwhelm people who are not data scientists.

30. Sometimes the code gets in the way - the prescriptive filters or scripts used to generate graphics are not transparent, and any errors caused by the software are not readily apparent.
31. Slow internet connections could be a problem.
32. We benefit from being able to link our constituents graphically to their watershed as well as to be able to allow place this information on our website and make it interactive.
33. Making sure that those who want the info have the necessary hardware, web access, and skills to use the web GIS.
34. Despite challenges, I think webGIS is still a very useful educational tool for water quality issues and can reach a younger audience who are more web-savvy